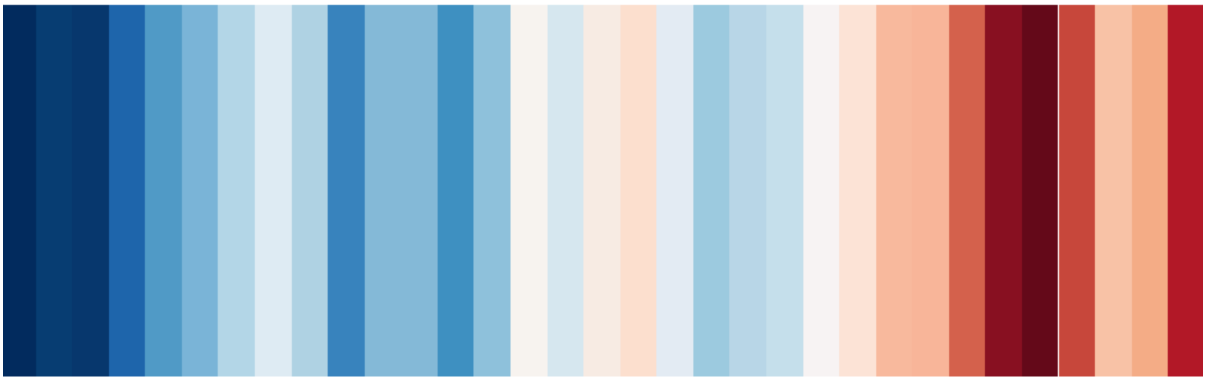

Swiss Permafrost Bulletin 2019/2020

Published by the Swiss Permafrost Monitoring Network PERMOS

March 2021

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Editors

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

Review

Members of the PERMOS Scientific Committee

Citation

PERMOS 2021. Swiss Permafrost Bulletin 2019/2020. Noetzli, J. and Pellet, C. (eds.). 21pp. DOI: 10.13093/permos-bull-2021.

Data availability

All PERMOS borehole temperature data are subject to the PERMOS Data Policy (open access for non-commercial use) and available online via http://permos.ch/data.html. This report is based on the PERMOS data set http://doi:10.13093/permos-2021-01.

Cover page

Warming stripes plotted for the mean annual permafrost temperatures at 21.56 m depth in the borehole COR_0287 in rock glacier Murtèl-Corvatsch.

Summary

The warming trend in Alpine permafrost observed over the past two decades continues and is accentuated in the hydrological year 2019/2020. This is shown by more than 20 years of observations in the framework of the Swiss Permafrost Monitoring Network PERMOS: the ground temperatures measured near the surface and at depth reached record values at most of the sites, as well as the active layer thickness and the rock glacier velocities.

The year 2019/2020 was the warmest year in Switzerland above 1000 m since the start of the measurements. The winter was particularly warm, with temperatures up to 1°C higher than the average of recent years. It was followed by a very warm spring, especially from mid-March to April, and a summer that was marked by two heat waves. At high elevations, the snow arrived early in November 2019, was about average thick during winter and disappeared comparably early in spring.

Ground temperatures measured near the surface in 2019/2020 were as high or even above the record level of the previous extremely warm years 2003, 2015 and 2018. This is the result of high air temperatures together with the early onset of snow, which insulated the ground from cold atmospheric conditions. The warm surface conditions resulted in new record values of active layer thickness (ALT) in all boreholes of the PERMOS Network that could be evaluated. ALT in the year 2020 ranged from 2.8 m (Flüela, GR) to 11 m (Schilthorn, BE). The increase in ALT compared to 2019 amounts to a few centimetres to almost half a metre depending on the location.

The almost continuous very warm surface conditions over three years resulted in increasing permafrost temperatures. The temporary interruption of the warming trend following winter of 2016 and 2017 is definitely over. Temperatures measured at 10 and 20 m depth have reached, and in some cases even exceeded, the previous record values measured in 2015. After more than 20 years of measurements, increasing permafrost temperatures are observed at all sites of the PERMOS Network. At the Stockhorn near Zermatt (VS), the permafrost temperatures at a depth of 20 m increased by about 0.8°C over 20 years, which is comparable to the observations at Murtèl-Corvatsch in the Upper Engadine (+0.5°C/10 years).

The kinematics of rock glaciers (masses of rock debris and ice moving downstream) indirectly reflect the permafrost conditions as the changes in rock glacier velocities follow the permafrost temperatures: when permafrost temperatures increase, rock glaciers generally accelerate. In 2020, rock glaciers accelerated significantly with an average increase in velocities of +21% compared to 2019 and are as high or higher than measured in the record year 2015.

Near-surface and deep temperatures have reached new records at many of the sites, as have active layer depths and rock glacier velocities. All measurements agree that the temporary pause in warming that followed the winter of 2016-2017 is definitely over. The observations in the year 2019/2020 are the result of persistent warm conditions over the past decades and the trends observed today are likely to continue.

1 Introduction

The Swiss Permafrost Bulletin is published annually by the Swiss Permafrost Monitoring Network PERMOS. PERMOS presents and assesses the most recent observations related to state and changes of permafrost in the Swiss Alps based on the measurements obtained the framework of the network. This second issue covers the hydrological year 2019/2020.

The PERMOS observation strategy is based on field measurements of three key elements, which complement each other to deliver a comprehensive picture of state and changes in mountain permafrost in the Swiss Alps: 1) ground temperatures near the surface and at depth (including meteorological observations), 2) changes in ground ice content, and 3) surface velocities of rock glaciers. The observation strategy follows a landform-based approach because differences in the permafrost evolution due to topography, ground ice content and snow regime are considered more important in the small country than those due to varying climate conditions (PERMOS 2019). Currently, PERMOS counts 15 borehole sites with 1 to 4 boreholes per site and 6 weather stations, 22 ground surface temperature (GST) sites with ca 250 miniature temperature dataloggers, 5 ERT sites, and 15 kinematic sites with 1 to 2 rock glaciers per site and 8 permanent GNSS (Figure 1.1).

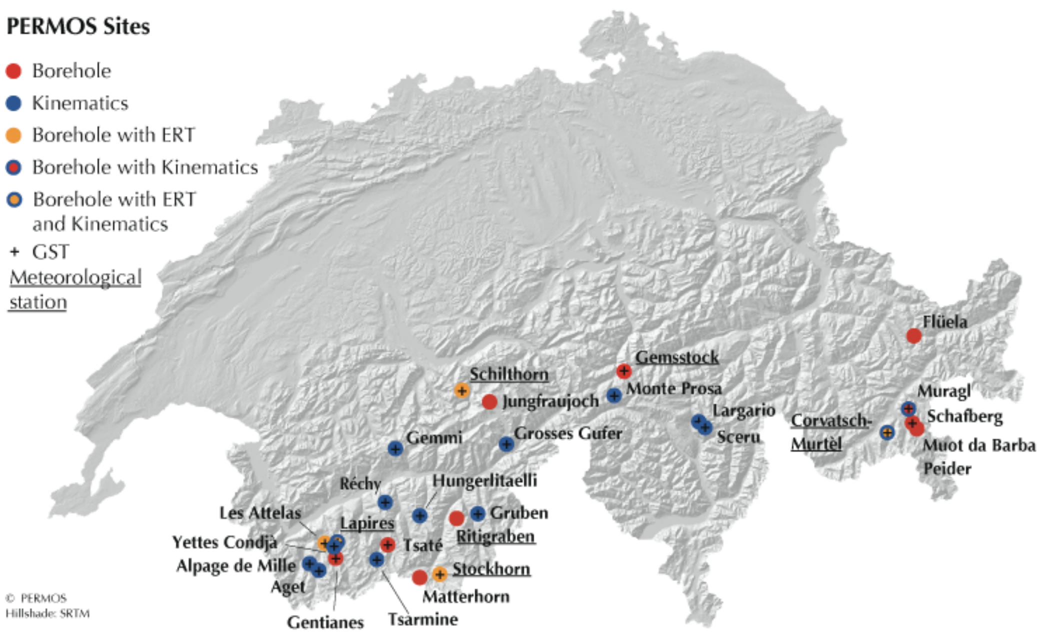

Figure 1.1: PERMOS field sites and measurements.

PERMOS is financially supported by the joint partnership of 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 the WSL Institute for Snow and Avalanche Research SLF) are responsible for both fieldwork and data collection. The PERMOS Office manages and administers the network, develops and implements the scientific monitoring strategy, manages 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). PERMOS is a component of the Global Terrestrial Network for Permafrost (GTN-P) of the Global Climate Observing System (GCOS).

2 Weather and climate

Air temperature and snow cover are the meteorological variables with the largest influence on the seasonal and inter-annual variations of the ground thermal regime. Air temperature drives the changes in the energy balance at the ground surface in periods with only little or no snow. A thick snow cover insulates the ground from the atmospheric conditions. Hence, the timing of the first snow fall in early winter and the time when the ground surface becomes snow free in spring are most relevant for permafrost monitoring. The weather and climate information presented here is based on MeteoSwiss (2020, 2021) and Trachsel et al. (2020).

The year generally was as warm as the previous record year 2018 in Switzerland, with new records for several stations at high elevations, e.g., the Jungfraujoch at ca. 3500 m asl. The hydrological year 2019/2020, which corresponds to the period of this report, was even the warmest ever recorded for operational weather stations above 1000 m asl. (Figure 2.1). This was due in particular to the warm winter and spring: Autumn 2019 was the sixth warmest observed since 1864, particularly in October and in the South. Winter 2019/2020 was the warmest ever measured with temperatures regionally 1 °C higher than the previous record. It was followed by the third warmest spring, which was especially dry and sunny between mid-March and end of April. Summer 2020 was characterized by two moderate heat waves end of July and in August. It was not as warm as the previous three particularly hot summers, but still warmer than the mean 1991–2020. Finally, September was again mild, dry and sunny. In October, unusually early snow fall led to an early start of the winter 2020/2021.

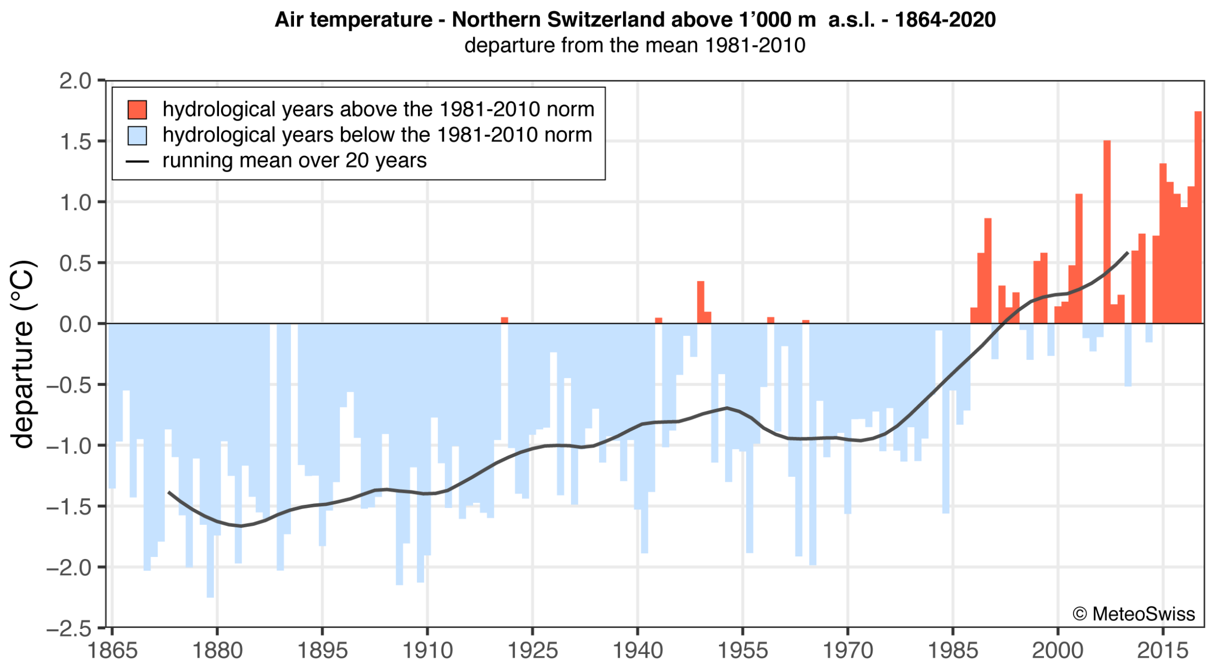

Figure 2.1: Air temperature deviation from the norm 1981–2010 based on homogenized data series for Swiss stations above 1000 m asl. and hydrological years. Adapted from MeteoSwiss (2021).

At higher elevations, the onset of the snow cover started early in November 2019. After a dry period in January 2020, intense periods of precipitation with major snowfalls occurred in February (mainly in Valais) and in early March. The rest of the winter was mainly dry and sunny. Snow heights were clearly below average at low elevations. Snow heights at high elevations, i.e. in the permafrost regions, were average (Engadine and eastern Alpine North Slope) or slightly above average (Southern Valais and Ticino). Due to the dry and mild spring, snow melt started rather early in 2020, but was slowed down by repeated snow falls at high elevations in June. The snow melt occurred about 1 to 4 weeks earlier than average.

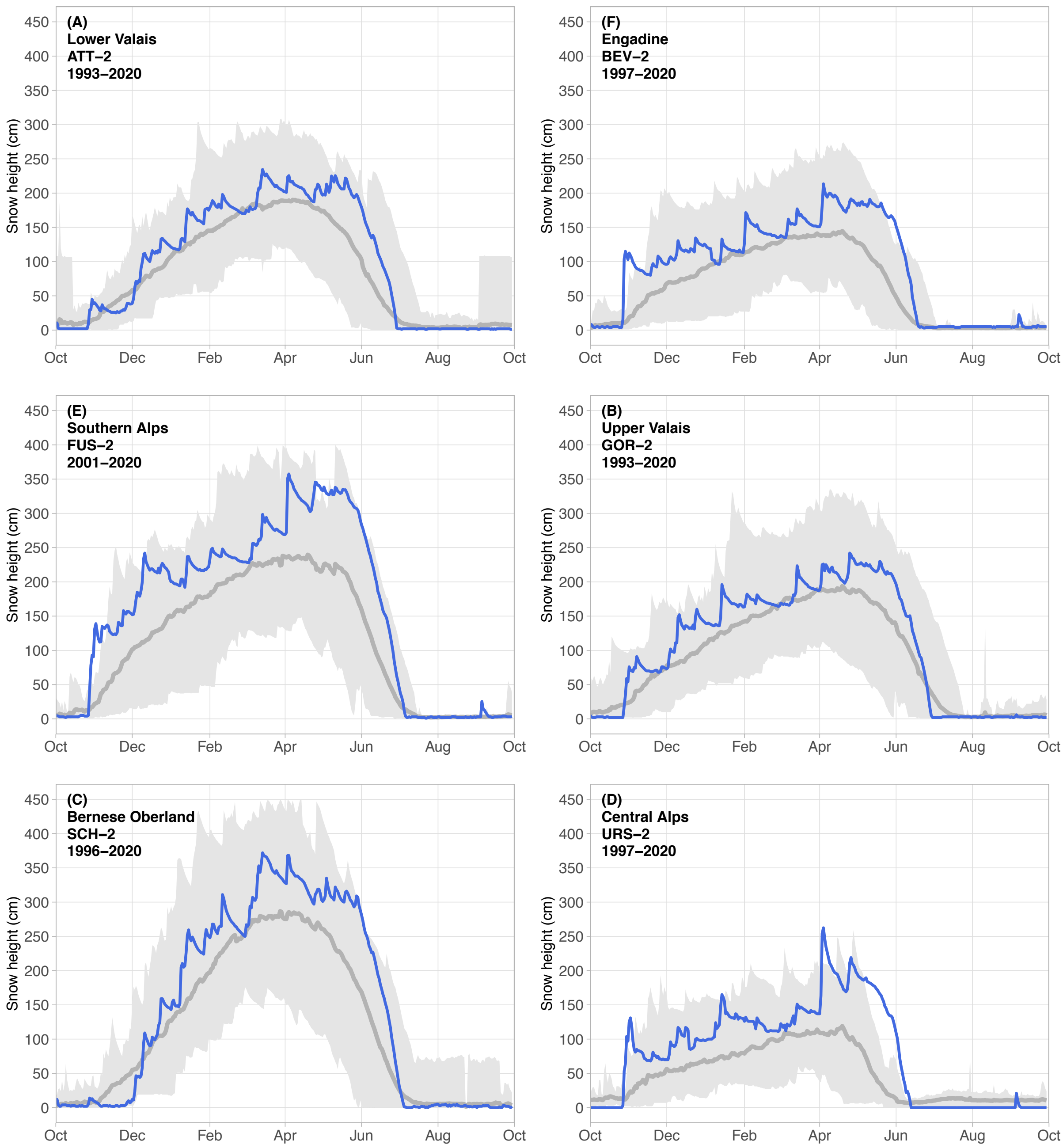

Figure 2.2: Snow height at six IMIS stations during winter 2020 (blue line) compared to the mean (thick grey line) and range (light grey shaded area) of the entire measurement series. Data were corrected for outliers and aggregated to daily mean values for plotting. The stations were selected to represent different permafrost regions in Switzerland: A) Lower Valais, B) Upper Valais, C) Bernese Oberland, D) Central Alps, E) Southern Alps, and F) Engadine. Data source: IMIS/SLF.

3 Thermal state of permafrost

Ground temperatures are the only direct, quantitative and comparable thermal observations of permafrost conditions and constitute the basis of long-term climate-related permafrost monitoring. When permafrost temperatures approach 0 °C in ice-bearing permafrost, however, hardly any temperature changes can be observed because of latent heat uptake during ground ice melt. Additional measurements that are sensitive to changes in ground ice and unfrozen water content are required to observe changes in the permafrost until the frozen material has thawed completely (see Chapter 4). Continuous ground temperatures, i.e., permafrost temperatures, are automatically logged in boreholes of at least 20 metres depth. The point information from boreholes is complemented by spatially distributed temperature measurements at the ground surface, i.e., ground surface temperatures (GST).

3.1 Ground surface temperatures

Ground surface temperatures (GST) are continuously recorded at 17 sites in the PERMOS Network with a temporal resolution of 1–3 hours. About 5–15 miniature data loggers are installed at each site at locations with different topographic settings to capture the spatial variability of near surface thermal conditions. The loggers are buried a few decimetres below the ground surface to shield them from direct solar radiation and to avoid warming of the instrument casing. Based on the GST measurements the thermal conditions at the ground surface can be described, which then penetrate to depth. In addition, the timing of the snow cover can be derived from GST time series based on the dampening of their temporal variability during times when the ground is snow covered and the zero-curtain effect during snow-melt.

In the year 2020, the GST data could only be collected from about half of the sites because of the unusually early onset of the snow cover at the beginning of October. There are no data for 5 sites and for 6 sites data are incomplete. The missing data will be collected in late spring or during the next field season. The results presented here are therefore based on the available data and may be biased to the Lower Valais, where data are most complete for the reporting period.

GST were above the average of the previous measurements during the entire year at all sites (Figure 3.1, left panels). This is well visible in winter, when GST hardly vary during the day due to the insulating snow cover. The Ground Freezing Indices (GFI, i.e. annual sum of the negative daily temperatures) show higher values than in previous years additionally indicating a warm winter at the ground surface. The Ground Thawing Indices (GTI, i.e. annual sum of the positive daily temperatures) during the year 2019/2020 cannot yet be conclusively assessed because most of the data available were collected in August or September. However, from the preliminarily results we can assume that the GFI will be similar or a little bit above the value observed in 2019.

The long-term evolution of GST is shown in Figure 3.2 using a running annual mean of ground surface temperature (MAGST). In the year 2020, MAGST were higher or comparable to the previous record level reached following the extremely warm years 2003, 2015 and 2018 (cf. Fig. 2.1). The MAGST remained at a high level for the past three years, following a short period with lower GST after the snow-poor winter 2016/2017.

The MAGST is above 0 °C at most of the PERMOS sites. This points to the importance of the so-called thermal offset. The temperature at the ground surface can be higher than the temperature at the permafrost table because of differences in thermal conductivity between frozen and thawed material as well effects of non-conductive heat transport in the active layer. Further, the permafrost conditions at depth are not in a thermal equilibrium with the current climatic setting (represented by the MAGST).

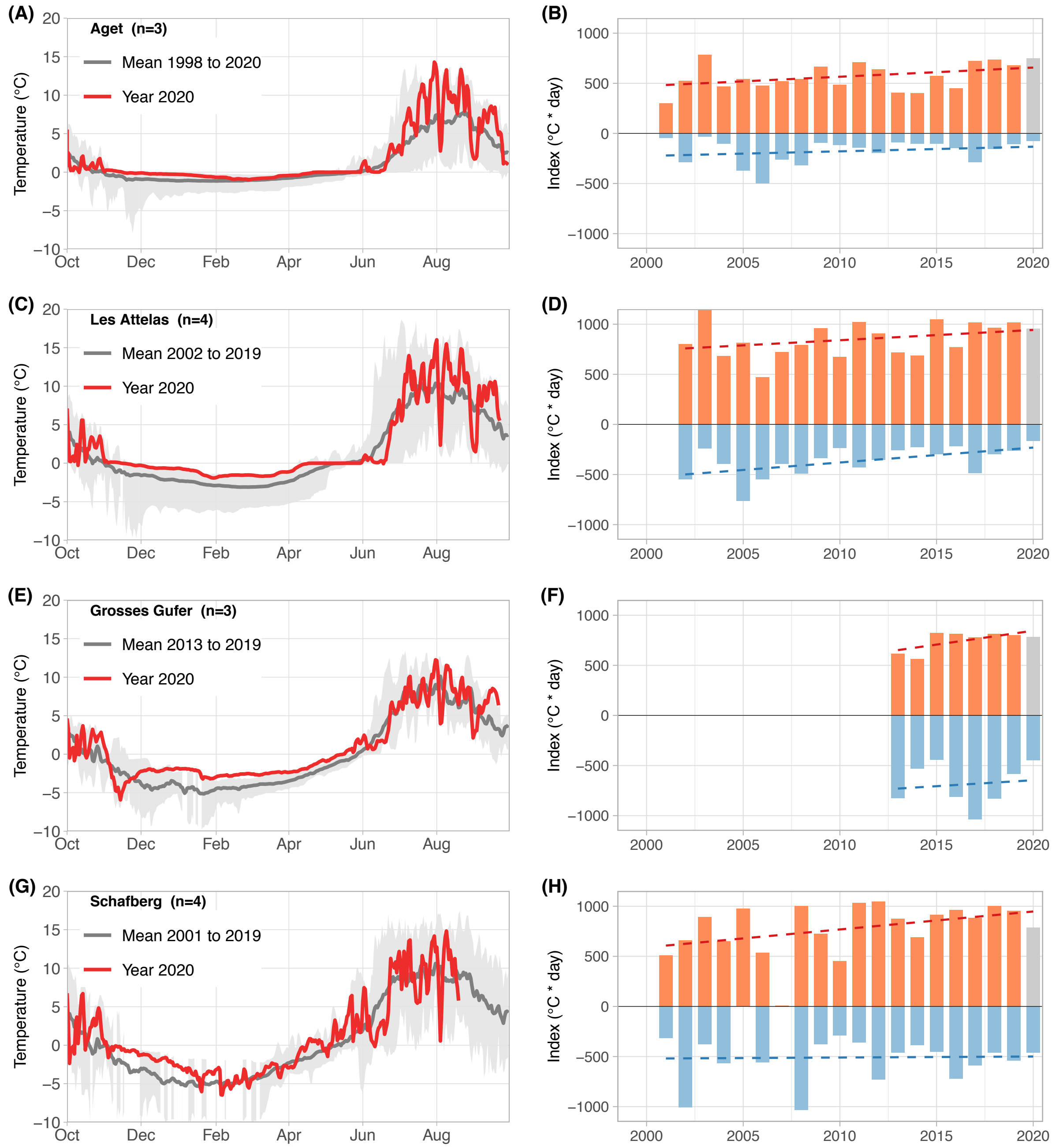

Figure 3.1: Daily mean ground surface temperatures during the hydrological year 2019/2020 compared to previously recorded temperatures (grey shades, left) and Ground Freezing and Thawing Indices (GFI and GTI, right) at five sites: rock glacier Aget in the Lower Valais (A,B), talus slope Les Attelas in the Lower Valais (C,D), rock glacier Grosses Gufer in the Upper Valais (E,F), and rock glacier Schafberg in the Engadine (G,H). The number in brackets indicates the number of individual GST time series used to calculate a site mean (left). The dotted lines indicate the linear trend since the beginning of the measurements (right). GTI for the year 2020 are shown in grey because the available data end before the end of the reporting period and the actual values will be higher.

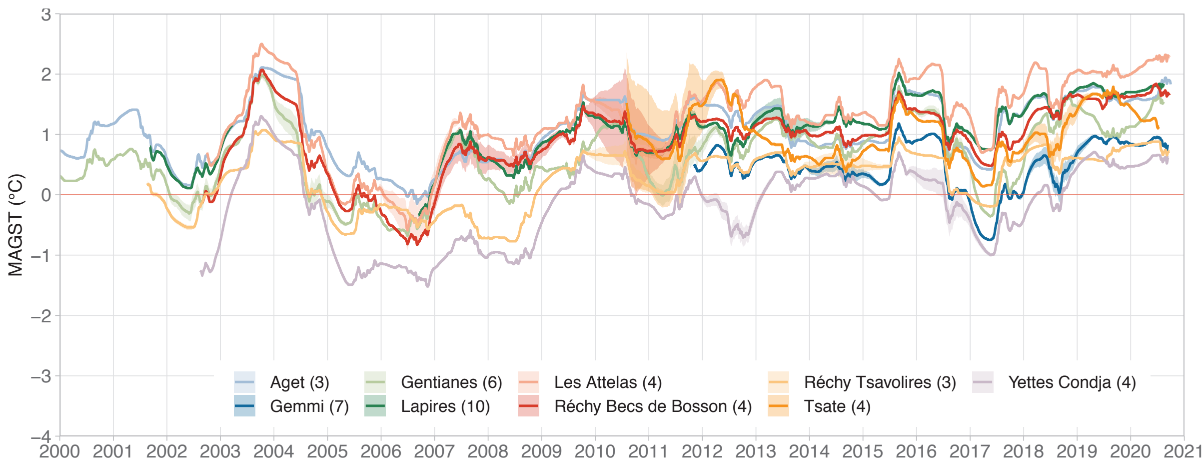

Figure 3.2: Site means of the running mean annual ground surface temperature (rMAGST) for the Lower Valais region. The number of individual GST time series used to calculate the mean of a site is given in brackets. The shaded areas illustrate the estimated uncertainty range resulting from gap-filling (Staub et al. 2017).

3.2 Active layer thickness

The maximum depth of the summer thaw is called the active layer thickness (ALT). It reflects the snow and atmospheric conditions during the current and previous year. The ALT is determined by linearly interpolating the borehole temperatures measured at the lowermost sensor in the active layer and at the uppermost sensor in the permafrost. However, freeze/thaw processes are not linear and therefore quantitative changes in ALT should be interpreted with care. ALT values are more precise if the value is close to the upper sensor. The qualitative changes and general trend are however considered robust.

Figure 3.4: Active layer thickness (ALT) derived from borehole temperature data for the Attelas talus slope in the Lower Valais (ATT_0108), the Stockhorn Plateau (STO_6000) and the Ritigraben rock glacier (RIT_0102) in the Upper Valais, and the summit crest on Schilthorn (SCH_5198) in the Bernese Alps. The uncertainty bars represent the thermistors used for the interpolation. Grey colors indicate a guess of the ALT because of data gaps or questionable data quality.

The ALT could be determined for 14 boreholes at 8 sites for the year 2020. It could not be calculated at boreholes not measuring an active layer or where data are manually collected in summer (i.e., before the penetration of the summer thaw has reached its maximum depth).

The warm near-surface conditions described above led to new record ALT in 2020 for all boreholes with available data (Figure 3.4). Depending on the site conditions, the ALT ranges from 2.8 m (Flüela) to 11 m (Schilthorn). In 2020, the ALT increased by a few centimetres (Flüela) up to around half a meter (Lapires, Schilthorn) compared to the previous year. The ALT were reached between mid-August (Murtèl-Corvatsch) and end of the year (Lapires, Schilthorn). For most sites, the date of the ALT in 2020 was around 10 days earlier than in 2019. In borehole SCH_5198 on Schilthorn the ALT amounts to 11 m in 2020 (compared to 4.4 m at the beginning of the measurements in the year 1998). This is a new record value of an observed ALT within PERMOS. Two other boreholes on Schilthorn have an ALT in 2020 of 11 m (SCH_5200) and more than 8 m (SCH_5318), supporting this high value. Despite this deep active layer, the ground is still refreezing in winter and no talik has developed so far (Figure 3.5). At Stockhorn STO_6000 the ALT increased in 20 years from 3.2 m to nearly 5 m in the year 2020. Even in the ice-rich rock glacier Ritigraben, the ALT increased by a meter during this time from 3.8 to 4.8 m.

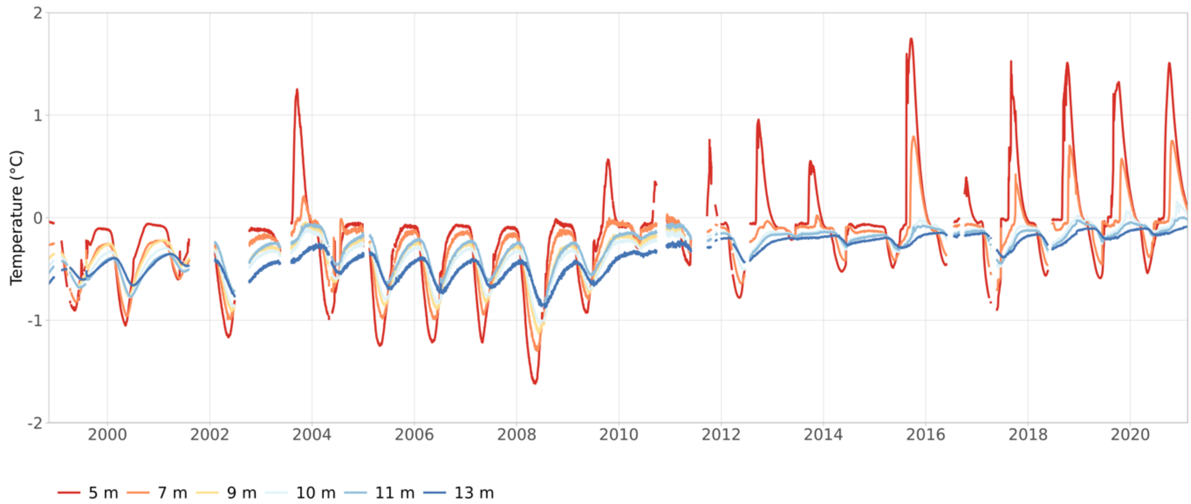

Figure 3.5: Daily mean values of borehole temperatures measured at depths between 5 and 13 m in borehole SCH_5198 on Schilthorn (Bernese Oberland, 2910 m asl.).

3.3 Permafrost temperatures

Diurnal temperature fluctuations occur in the uppermost 1–3 metres, whereas ground temperatures below the depth of the zero annual amplitude (ZAA) react with a considerable delay to multi-annual trends connected with changing climatic conditions. The depth of the ZAA is at around 15–20 m for sites in the European Alps. Measurements between the first metres below the surface layer and the depth of the ZAA are used to describe seasonal variations or effects of extreme weather periods. The most important factors influencing the temperature evolution at depth are the temperature range (colder ice-bearing sites exhibit faster warming), the ground ice content (latent heat effects reduce temperature changes) and the timing of the winter snow cover (an early snow cover conserves the heat in the ground while a long-lasting one insulates the ground from higher air temperatures in early summer). Here we report on the temperatures at 10 and 20 m depth to describe the changes in permafrost conditions in the Swiss Alps.

Figure 3.1: Rock fall close to the Murtèl-Corvatsch rock glacier during field work on 27. August 2020. Photos: D. Amschwand.

There is an overall warming trend observed at 10 and 20 m depth since the beginning of the measurements. This trend, has been especially pronounced since 2010 and was temporarily interrupted after winter 2017. Sites with colder permafrost conditions (e.g. Stockhorn, Murtèl-Corvatsch and Matterhorn) show a stronger warming, which is consistent with observations from permafrost regions worldwide (Biskaborn et al. 2019, Etzelmueller et al. 2020, Noetzli et al. 2020). The permafrost temperatures at Murtèl-Corvatsch (Figure 3.1) increased by more than 0.5 °C at 20 m depth and by more than 1 °C at 10 m depth during the 3 decades of observation. Permafrost temperatures at Stockhorn (Figure 3.2) increased by ca. 0.4 °C at 20 m depth and by ca. 0.8 °C at 10 m depth during the past 2 decades, which is comparable. At sites with permafrost temperatures close to 0 °C (e.g. Schilthorn, Lapires or Schafberg), the observed temperature increase is significantly smaller due to the uptake of latent heat during phase change (Figure 3.3).

Figure 3.2: PERMOS site on the Stockhorn Plateau above Zermatt, VS at 3400 m asl. In the right part of the picture, the borehole and the weather station are visible, in the middle of the background the Lyskamm and to the left of it the Monte Rosa (with clouds) can be seen. Photo: A. Hasler.

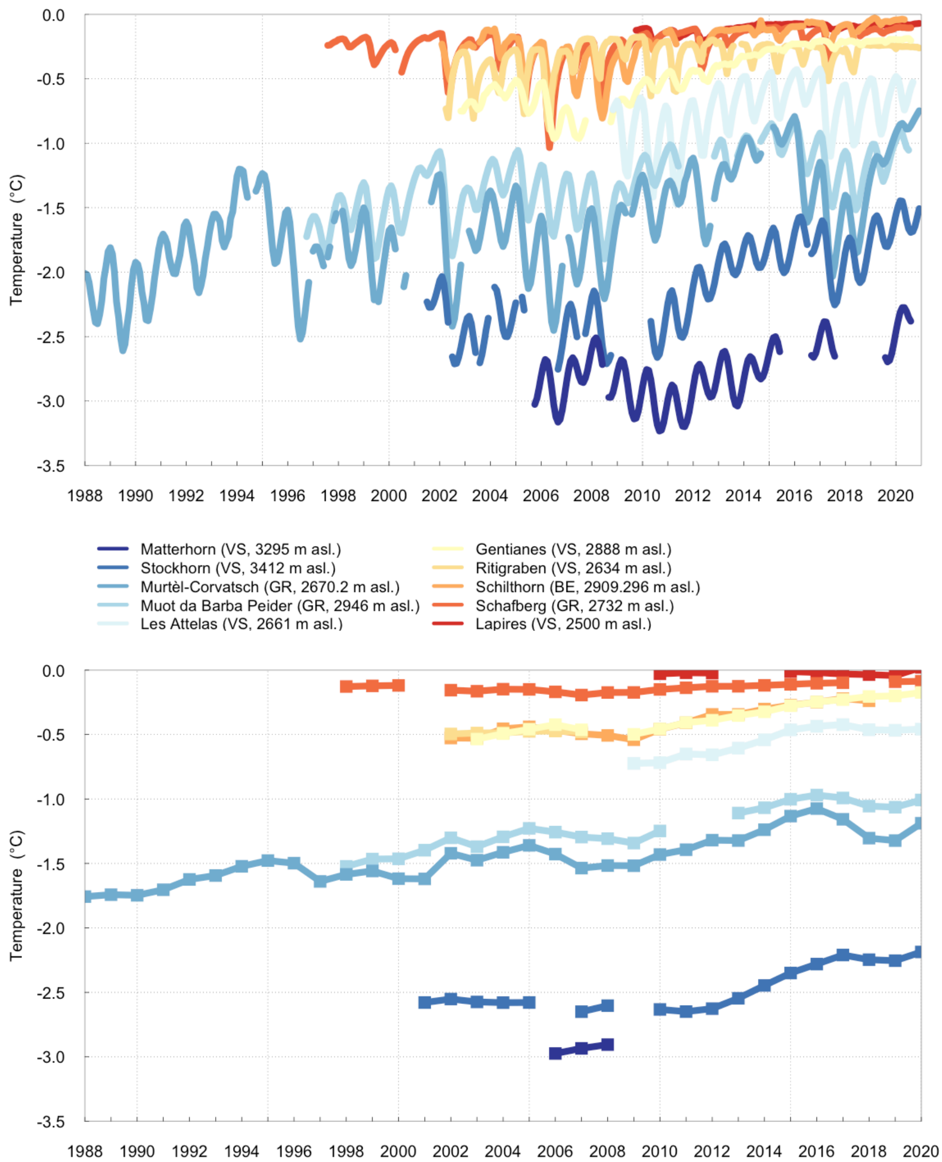

Figure 3.6: Permafrost temperatures measured in selected boreholes at 10 m (monthly means, top) and 20 m depth (means of the hydrological year, bottom).

4 Electrical resistivities

Electrical resistivity tomography (ERT) surveys are important complements to ground temperature measurements given their sensitivity to changes in the unfrozen water and ground ice content. ERT is particularly valuable at sites where permafrost temperatures are close to 0 °C. Here, increased energy input from the surface does not result in a significant increase in ground temperature due to the latent heat required for ground ice melt. Changes in electrical resistivity are observed using repeated ERT surveys and can be related to the changes in the content of ground ice and liquid water: decreasing electrical resistivities indicate an increase of the ratio between liquid water and ice content. In general, an increased resistivity indicates a decrease in the overall ground ice content. Conversely, increasing electrical resistivities indicate a decrease of the ratio and an increase of the ground ice content.

The electrical resistivities measured at five of the PERMOS sites span over several orders of magnitudes (Figure 4.1). The lowest resistivities (~3’000 Ωm) are found at Schilthorn, which is characterized by a weathered bedrock subsurface, low ground ice content and near-zero permafrost temperatures. Conversely the highest resistivities (~300’000 Ωm) are measured on the rock glacier Murtèl-Corvatsch, characterized by high ground ice content and permafrost temperatures around –1.5 °C.

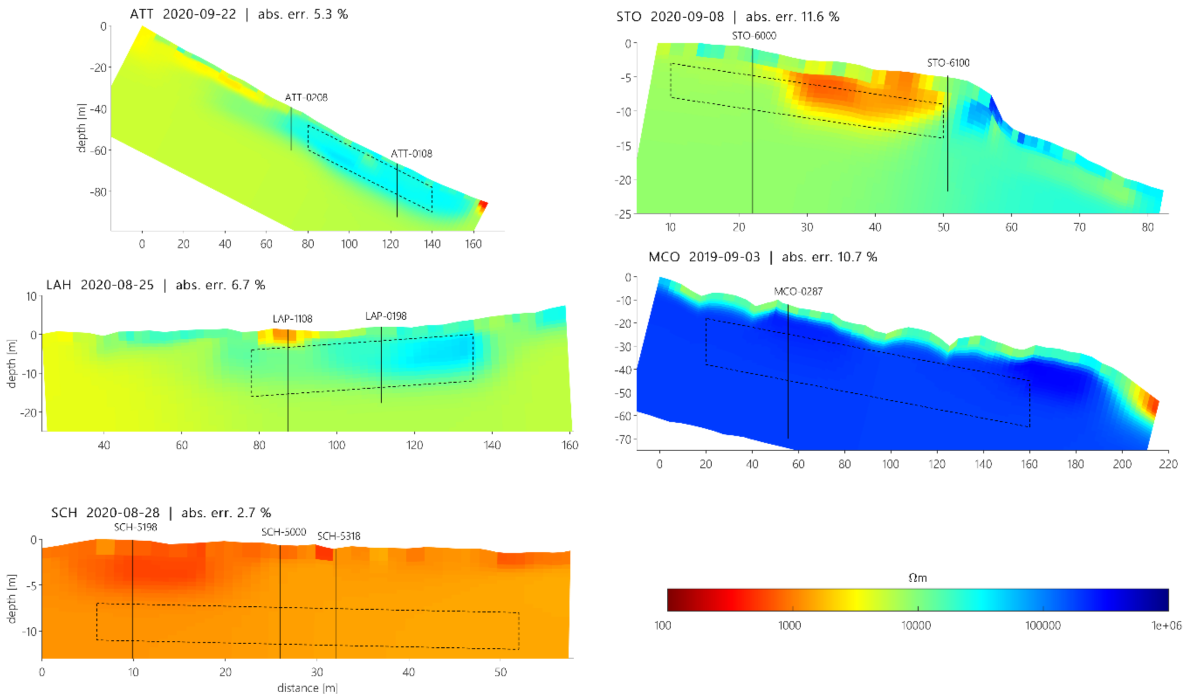

Figure 4.1: ERT-Tomograms showing the resistivity distribution in 2020 at the five PERMOS ERT profiles (note the different year at Murtèl-Corvatsch because of bad data quality in 2020). The representative zones used for the time series in Figure 4.2 are indicated with dashed boxes.

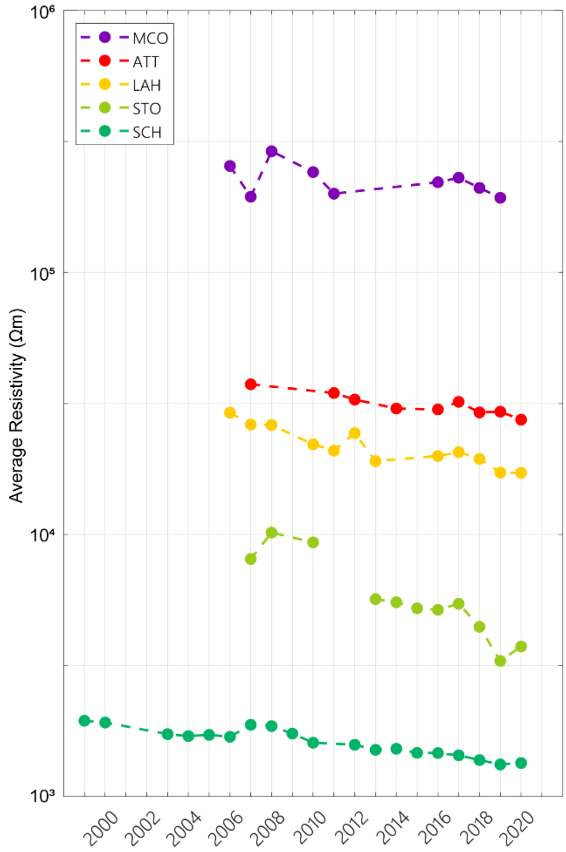

Figure 4.2: Average electrical resistivities of the permafrost zone (see Figure 4.1) at the end of summer (August–September) for the 5 ERT sites.

Figure 4.2 shows the evolution of the electrical resistivity within the permafrost layer at the five sites for 1999–2020. A general decreasing trend is observed, which is consistent with the reported permafrost temperature increase (see Chapter 3). In 2020, different signals were observed: a strong resistivity increase at Stockhorn, a slight resistivity increase at Schilthorn and Lapires, and a slight resistivity decrease at Les Attelas. The data quality at Murtèl-Corvatsch was not sufficient for further analysis. These heterogeneous results can be due to several factors such as meteorological inter-annual variability (i.e. drier/wetter surface conditions), irregular measurement dates (i.e. not corresponding to the timing of the ALT) or inversion artefacts during the data processing. Mollaret et al. (2019) showed that the effects of these factors are typically smaller than the long-term climatic signal. That is, increasing resistivity values measured in 2020 cannot be considered as a trend interruption/reversal, particularly when comparing them to the increase in ground temperatures and ALT at these sites.

5 Kinematics

The kinematics of creeping permafrost landforms, such as rock glaciers, reveal indirect information about the ground thermal conditions. 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 of velocity, and conversely for decreasing temperatures). In the framework of PERMOS, surface velocities of rock glaciers are measured by annual terrestrial geodetic surveys (TGS) at the end of the summer (August-September) as well as by permanently installed GNSS devices. These methods are complementary and allow to capture the short-term and seasonal velocity variations (permanent GNSS) together with their spatially distributed annual and inter-annual changes (TGS).

5.1 Annual terrestrial geodetic surveys

The positions of selected boulders (10–100 points) spatially distributed on 18 rock glaciers lobes are measured each year. In 2020, the TGS measurements could not be carried out at two of the sites and are incomplete at four others due to exceptionally early snowfall in autumn (Figure 5.1).

Figure 5.1. GPS measurements on the snow-covered rock glacier Yettes Condjà in early October 2020. Photo: L. Perez.

The observation year 2019/2020 was characterized by a general velocity increase at all sites except for Yettes-Condjà C (YET2 in Figure 5.3) and Gruben. The mean of all sites increased by +21% compared to 2018/2019 (Figure. 5.3), which is similar to the acceleration between 2017/2018 and 2018/2019. The largest velocity increase was again observed in Central/Southern Alps region (+30% compared to 2018/2019 for the entire region). However, the velocity signal is very similar for all four regions (+23% in Lower Valais and Engadine and +15% in Upper Valais, Figure 5.3). This is consistent with the high ground surface temperatures (see Chapter 3). Absolute velocity values measured in 2019/2020 are comparable to or slightly higher than the 2015 maximum, thus ending the shorty recovery period that followed the temporary trend interruption in 2016/2017.

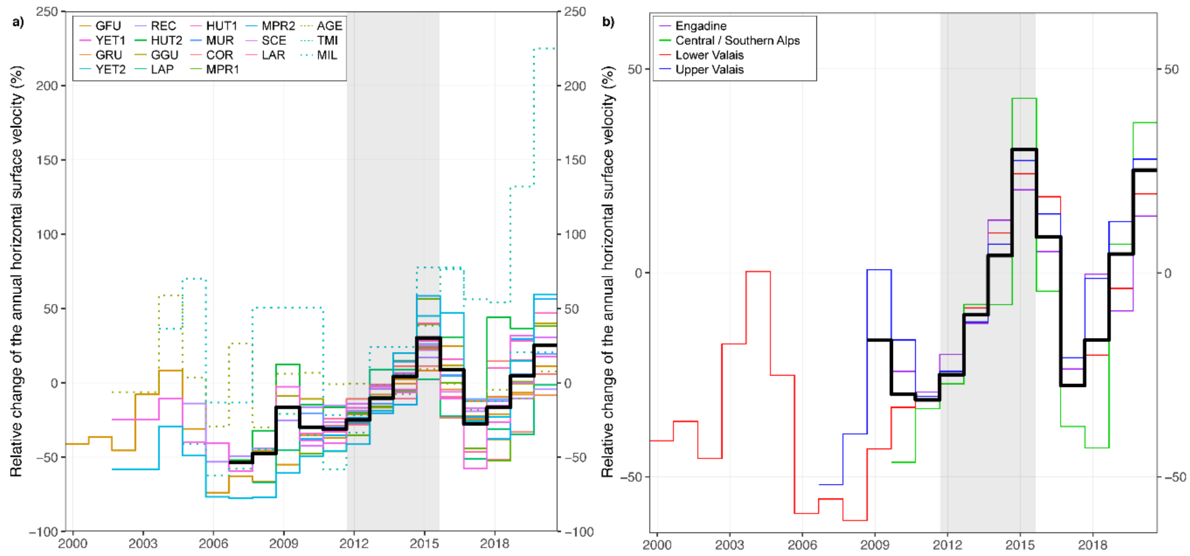

Figure 5.2: *Mean annual horizontal surface velocity derived from terrestrial geodetic surveys relative to the reference period 2012–2015 (grey area). Dotted lines represent the rock glaciers with atypical evolution and the black line represents the average of the Swiss Alps (excluding two atypical rock glaciers). Left: all 18 monitored rock glacier lobes (for site abbreviations see Table A.1). Right: average velocity for the four topo-climatic regions.*

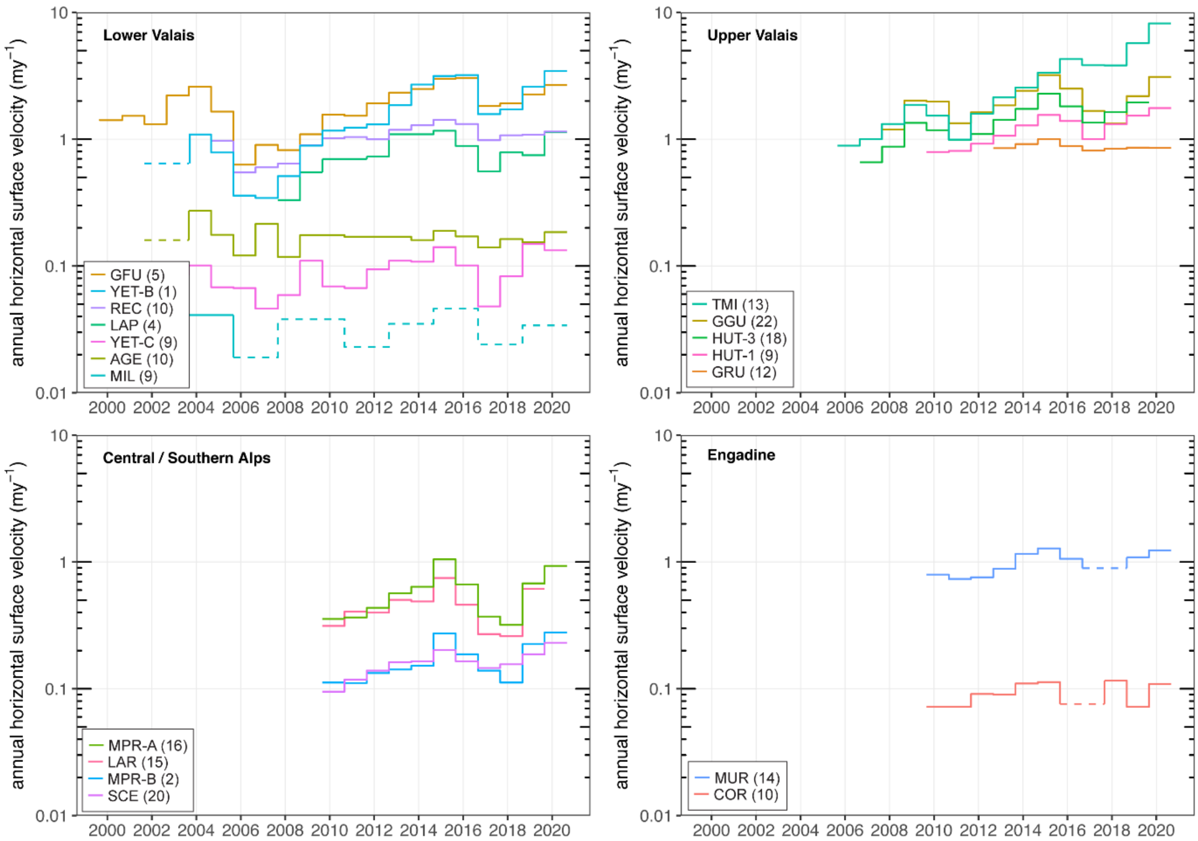

Figure 5.3: *Velocity pattern of 18 rock glacier lobes in the Swiss Alps divided into four topo-climatic regions. The number of reference points for each site is indicated in brackets and the dashed lines represent velocities measured over two years. The abbreviations for the site names can be found in Table A.1.*

Two rock glaciers do not follow this general pattern and present marked accelerating (Tsarmine, TMI) and decelerating (Aget, AGE) trends (Figures 5.2a, 5.3). A decelerating trend typically indicates in-situ permafrost degradation, whereas an exceptional acceleration indicates ongoing destabilization. In both cases, local factors (slope, hydrology, ground temperature, geometry, debris loading, etc.) become dominant and the rock glacier kinematics are no longer predominantly driven by the climate.

5.2 Permanent GNSS

Permanent GNSS measure daily positions of single boulders on 8 rock glaciers within the PERMOS network. The high temporal resolution provided by these instruments enables the computation of daily displacements, which are much smaller than the annual values. The reliability and significance of the small velocity variations (typically +/-0.1–0.2 my^{-1}) have to be interpreted with caution, since they depend on a wide range of factors, and may not be representative of the general rock glacier motion (e.g., snow pressure on the mast in winter, stability and anchorage of the boulder in the terrain). To ensure the reliability of the short-term velocity variations, measured positions are filtered to remove unreliable measurements, and daily positions are aggregated using a 14-days moving window. The displacements are calculated over a 14-days period.

Figure 5.4 shows the typical seasonal evolution of creep velocities for a rock glacier at the two sites Réchy and Monte Prosa: decreasing velocities in winter (minima reached end of April) followed by a strong acceleration at the beginning of summer (during snow melt) and peak velocities in September/October. After a strong acceleration in March 2018, the velocities at Monte Prosa in 2019/2020 are within the same range as those observed at Réchy and they follow the same seasonal pattern.

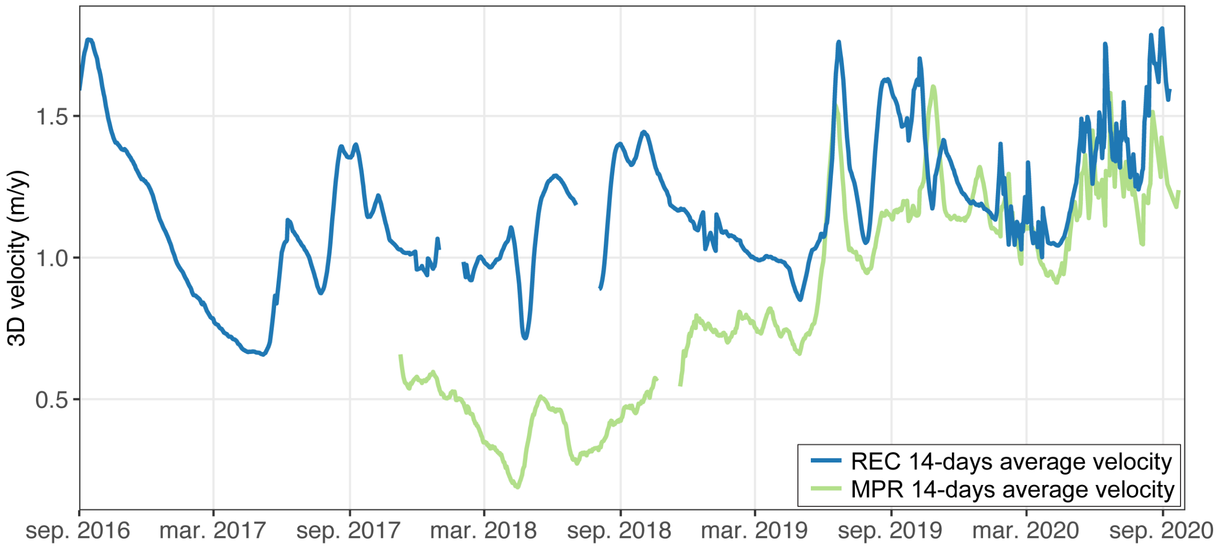

Figure 5.4: Evolution of the seasonal creep velocity at the Réchy (blue) and Monte Prosa (green) rock glaciers. The velocities are computed over a 14-day period using daily positions.

Similarly to 2018/2019, the end of summer acceleration was very pronounced in 2019/2020 with maximum velocities recorded at Réchy. Conversely to the winter 2018/2019, a velocity decrease was observed in 2019/2020 at Monte Prosa, which is consistent with the measured average GST. The common seasonal behaviour of these two rock glaciers also illustrate the homogeneously warm near-surface temperatures observed in all regions of the Swiss Alps (see Chapter 3.1).

6 Conclusion

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. The year 2020 was a remarkable year for permafrost in the Swiss Alps: PERMOS started in the year 2000 and celebrated its 20th anniversary, however, only with several reports and a few virtual events. However, there were no restrictions related to the COVID-19 pandemic on field work activities as elsewhere in permafrost regions. But data collection was hindered by the unusually early snowfall at the beginning of October 2020, which covered loggers or measurement points. Finally, the exceptionally warm hydrological year 2019/2020 led to many new record values observed for active layer thicknesses, permafrost temperatures and rock glacier velocities.

The hydrological year 2019/2020 was the warmest year ever recorded at higher elevation in Switzerland, which was due in particular to the warm winter and spring. Winter 2019/2020 started and ended earlier than average and snow heights at higher elevations were generally average. Summer 2020 was warmer than the mean of the past three decades, but not quite as warm as the three previous summers. The weather and climate conditions during the hydrological year 2019/2020 lead to the following permafrost conditions in the Swiss Alps (Figure 6.1):

- Ground surface temperatures are higher than average. For the past three years they were continuously at or above the level observed after the record years 2003, 2015 and 2018.
- New records for active layer thickness (ALT) were observed in 2020 for all boreholes in the PERMOS Network where data are available. On the summit crest of the Schilthorn, the ALT in 2020 was 11 m. This is the deepest active layer ever observed in the Swiss Alps.
- The permafrost temperatures measured in boreholes are increasing since the temporary cooling following the snow-poor winter 2017. In 2020, they are back at or close to the previous maximum from 2015.
- Heterogeneous signals of permafrost resistivities were observed at five borehole sites in 2020 with both increase and decrease. The interpretation of these signals requires further measurements in 2021 and onwards.
- A strong increase of rock glacier surface velocity by +20 % compared to the values in 2019 was measured, reaching new record values at some sites.

All the observations elements show a consistent picture of continued warming and degradation of permafrost in the Swiss Alps during the observation period 2019/2020. This tendency is, however, not only a result of the extremely warm year 2019/2020, but of persistent warm conditions observed for several years to decades. The observations reported in this bulletin follow a longer lasting trend, which is not foreseen to stop in the coming years. The warm conditions observed in the uppermost metres will continue to penetrate to depth.

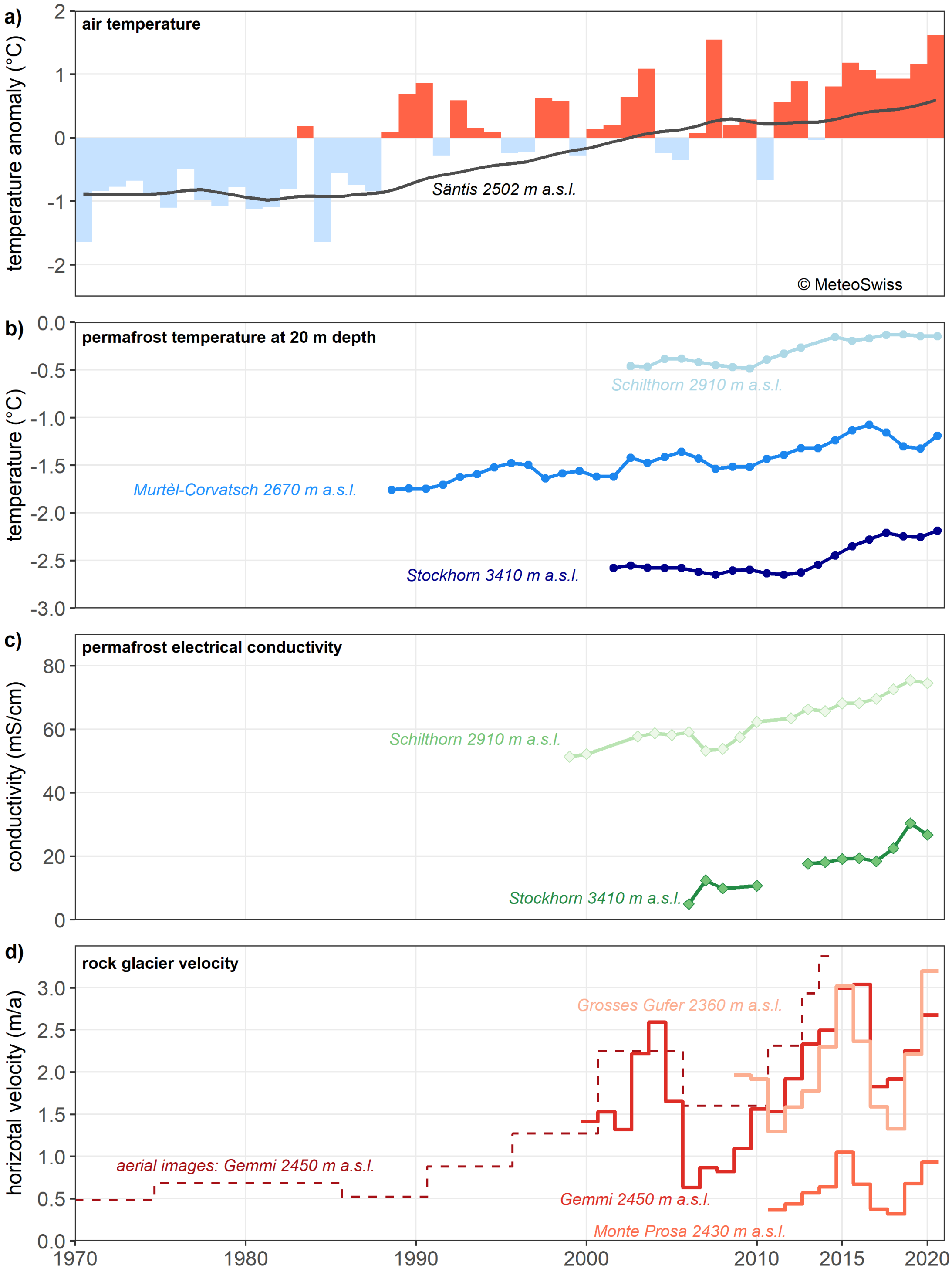

Figure 6.1: Evolution of the three key observation elements: annual mean temperatures at around 20 m depth (b), permafrost electrical conductivity (c), and rock glacier creep velocity (d). The data are compared to long-term air temperature observations (a, data source: MeteoSwiss).

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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		