Swiss Permafrost Monitoring Network
ETHZ, SUPSI, UniFR, UniL, UniZH, WSL-SLF

Swiss Permafrost Bulletin 2018/2019

Swiss Permafrost Monitoring Network PERMOS

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Contents

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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. The latest DOI is doi:10.13093/permos-2019-01.

Cover page

Front of the Tsarmine rock glacier in September 2019. Photo: C.Pellet

1 Introduction

This report on the state of permafrost in Switzerland presents and assesses the data obtained in the framework of the Swiss Permafrost Monitoring Network PERMOS during the hydrological year 2018/2019. Reports are published online every year as part of a revised communication strategy focused on timely access to the data, and printed in the traditional form every four years covering the periods of the 4-year PERMOS Agreements between the three financing partners and the six partner institutions.

PERMOS started 20 years ago with a 6-year pilot phase and evolved from unconsolidated, project-based field sites into a coherent and financially secured network through 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). This report therefore includes an overview of the achievements for the two decades of operational permafrost monitoring in the Swiss Alps.

The focus of the current 4-year period (2019–2022) is on the standardization and further operationalisation of both field and data processing procedures as well as on a strategy to secure long time series measured in boreholes at risk. The focus of the 4-year periods has changed from the implementation of the network (2007–2010) to its consolidation (2011–2014), to the set-up of the data management system (2015–2018).

The 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 is in charge of the implementation of the scientific monitoring strategy, the management and administration of the network, the data curing and management as well as the publication and communication of the results. Finally, two standing committees advise and supervise the network, politically and financially (Steering Committee) as well as scientifically (Scientific Committee, Fig. 1.1). PERMOS was an early component of the Global Terrestrial Network for Permafrost (GTN-P) of the Global Climate Observing System (GCOS).

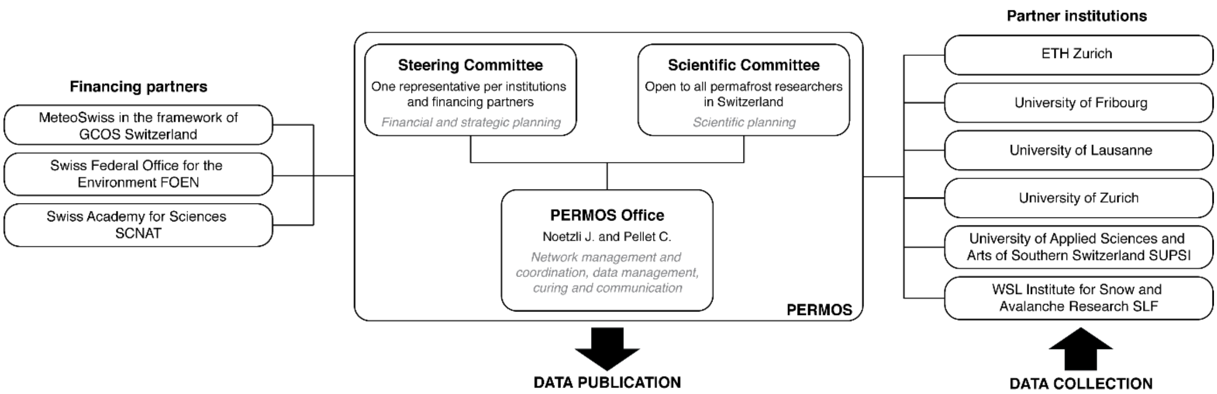

Figure 1.1: Organization of the PERMOS network.

The monitoring strategy as well as the number and location of the field sites have been evaluated and adapted continuously during the past two decades. Following scientific and technological progress, observation elements were replaced (i.e. Bottom Temperature of the Snow cover BTS) or added to the original measurements of permafrost temperature measured in boreholes and near-surface ground temperature (GST, Chapter 3). In 2005, repeated electrical resistivity tomography (ERT, Chapter 4) at selected borehole sites were included to assess changes in ice content within the permafrost, which cannot be observed based on temperature alone. Annual terrestrial geodetic surveys to measure permafrost creep velocities were added in 2007 (Chapter 4). Since 2019 permanent GNSS add a seasonal signal to the latter (Chapter 4) and weather stations at selected borehole sites deliver detailed meteorological data for the surface energy balance (Chapter 2). These observation elements complement each other to provide a comprehensive picture of permafrost changes in the Swiss Alps.

The scientific observation strategy is based on field measurements at sites with differing topographic settings and landforms. The most important characteristics influencing changes in permafrost are the topography, the ground ice content, as well as the timing and duration of the winter snow cover. The initial 9 boreholes sites and 10 GST sites were continuously expanded. Today, PERMOS counts 15 borehole sites (with 1 to 4 boreholes per site and 6 weather stations), 22 GST sites (with about 250 miniature temperature dataloggers), 5 ERT sites, 15 kinematic sites (with 8 permanent GNSS, Fig. 1.2).

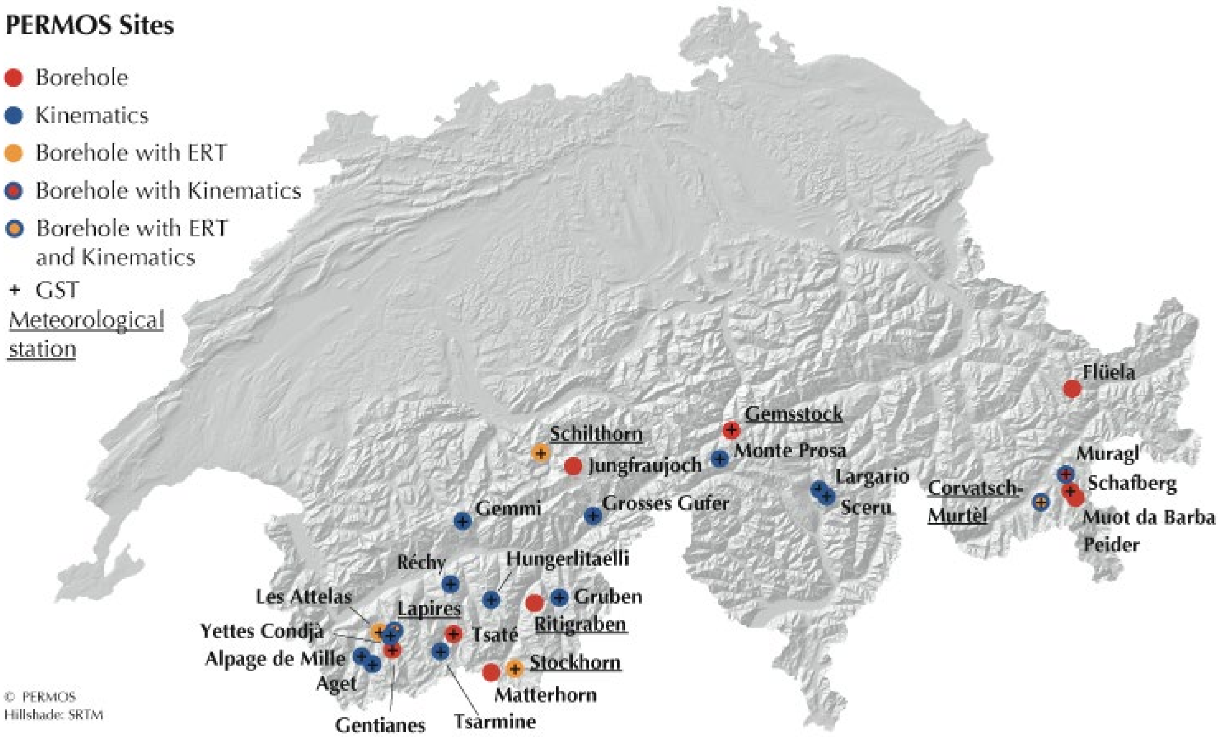

Figure 1.2: PERMOS field sites and respective measurements.

2 Weather and Climate

The series of higher than average warm years continued during the observation period 2018/2019, which was the fifth warmest year since the start of the measurements in 1864 (MeteoSwiss 2020, Fig. 2.1). October and November 2018 were exceptionally wet south of the Alps and in the Grisons region, which resulted in an early onset of the snow cover. In contrast, north of the Alps, autumn 2018 was very dry and snow fell only in December.

Winter (DJF) conditions were different south of the Alps compared to the rest of the Swiss Alps. South of the Alps, winter 2019 was the second warmest ever measured, with only 30–40% of the normal precipitation. In the rest of the Alps, temperatures were above average in December and February, whereas January was the coldest since 30 years. Regular and intense snowfall occurred throughout the winter. Thus, winter 2019 was snow-poor and very mild south of the Alps north and one of the most snow-rich winters of the past twenty years in the rest of the Alps (Zweifel et al. 2019, Fig. 2.2).

Large local snowfalls were recorded in the Southern, Eastern and Central Swiss Alps in April 2019. Together with lower than average temperatures in May, it led to a late melt-out of the snow cover at elevations above ca. 2500 m asl. (i.e. where the PERMOS sites are located). Most of the snow melt occurred in June 2019 and was rapid due to the very high temperatures in early summer 2019.

Summer (JJA) 2019 was the third warmest ever measured after 2015 and 2003 (with the second warmest June). Heat waves occurred at the end of June (7–10 days) and end of July (5–8 days). Unlike the extremely dry summers 2003 and 2018, the precipitation in summer 2019 was within the 1981–2010 norm.

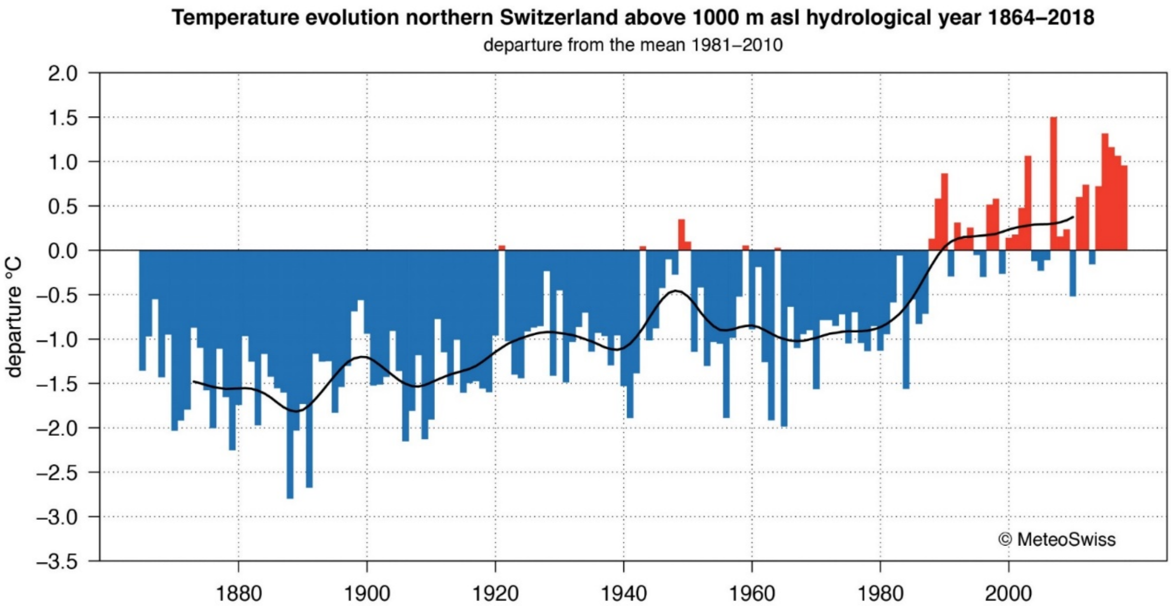

Figure 2.1: Air temperature deviation from the norm 1981–2010 based on homogenised data series for Swiss stations above 1000 m asl. and hydrological years. Reproduced from MeteoSwiss (2020).

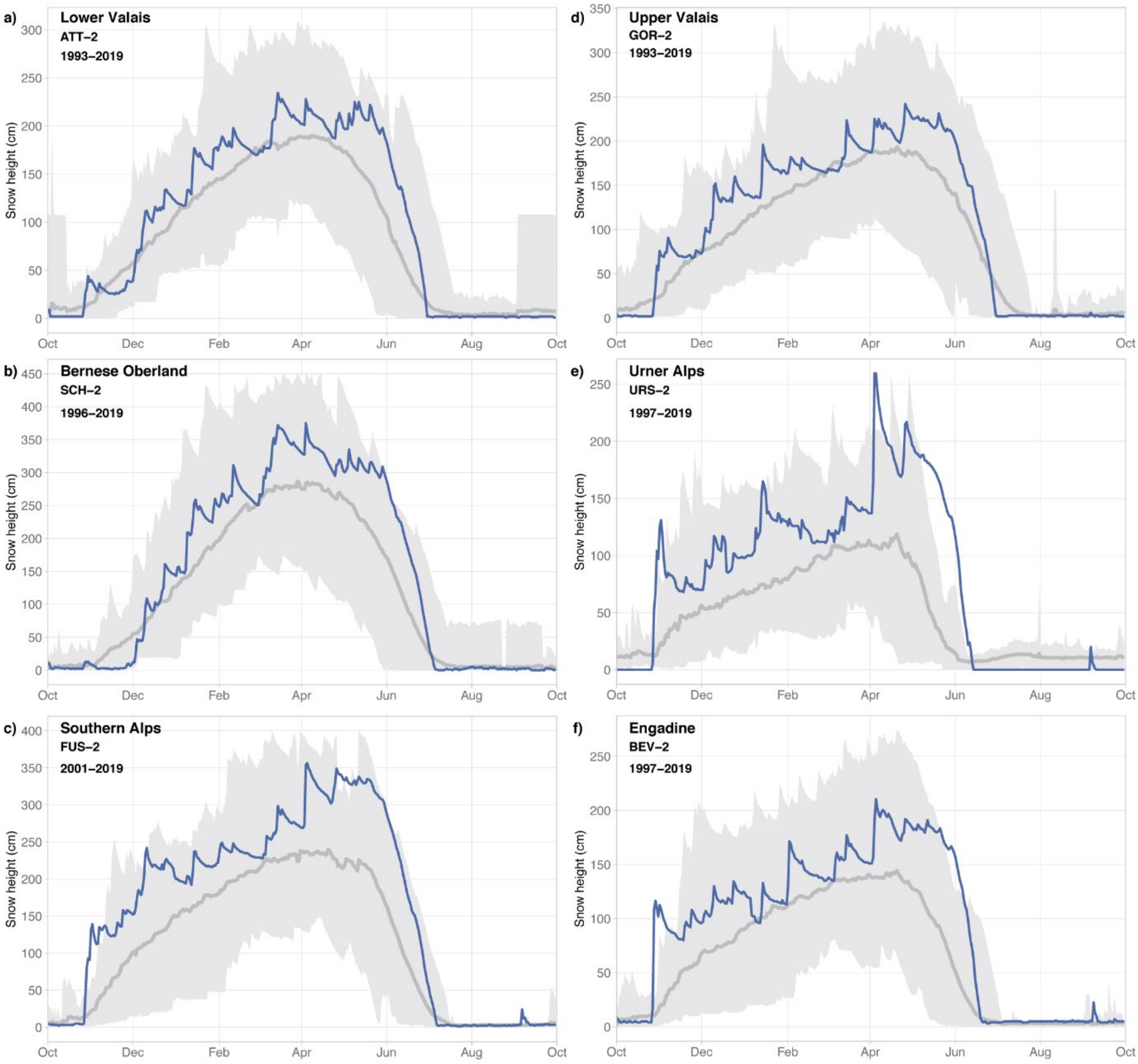

Fig. 2.2: Snow height at six IMIS stations during winter 2019 (blue line) compared to the mean (thick grey line) and range (light grey shaded area) of the entire measurement series. Data were corrected for outliers and aggregated to daily mean values for plotting. The stations were selected to represent different permafrost regions in Switzerland: a) Lower Valais, b) Bernese Oberland, c) Southern Alps, d) Upper Valais, e) Urner Alps and f) Engadine. Data source: IMIS/SLF.

3 Ground temperatures

Temperature measurements in boreholes of 20 m depth and more are the basis of long-term permafrost monitoring because they are the only direct observations of permafrost. The point information from the boreholes is complemented by recordings of ground surface temperature GST because their changes are the main drivers of changes in ground temperatures. Distributed GST measurements at the borehole sites help to characterize the spatial variability of the site and the representativeness of the borehole. GST are measured using miniature temperature dataloggers, which are placed a few decimetres below the ground surface to avoid rapidly fluctuating surface temperatures and warming of the instrument casing.

In the uppermost 1–2 metres, diurnal temperature fluctuations occur. At depths below the zero-annual amplitude (ZAA), the ground temperature is no longer subject to seasonal variations and represents multi-annual trends in connection with changing climatic conditions. The ZAA is in the range of 15–20 m for Alpine sites. Measurements in between, at around 10 metres depth, describe seasonal variations and effects of extreme weather periods with a delay of about half a year. The most important factors influencing the temperature evolution at depth are the temperature range (colder sites exhibit faster warming) and the ground ice content (latent heat effects cause zero curtains and delay temperature changes).

The maximum penetration of the summer thaw, called the active layer thickness (ALT), reflects the snow and atmospheric conditions during the current and previous year. It is defined by the maximum depth of the 0 °C isotherm in the ground during one year.

3.1 Ground surface temperatures

The geographically contrasting weather conditions observed in winter 2019 led to contrasting signals in GST. Above average temperatures were recorded throughout most of the winter in the Gotthard and Southern Alpine region (Fig. 3.1e), whereas the temperatures were close to the long-term average in the other regions (Fig. 3.1a and c). Similar observations can be made from the Ground Freezing Indices (GFI, i.e. annual sum of the negative daily temperatures). The Ground Thawing Indices (GTI, i.e. annual sum of the positive daily temperatures) during the year 2018/2019 showed uniform, warm summer conditions for all regions in Switzerland.

The GST indicated a comparatively late melt of the snow cover in all regions, which is consistent with the observed meteorological conditions. At Réchy and Largario (Fig. 3.1c and e), the effects of both recorded heat waves (end of June and end of July 2019) are clearly visible, whereas at Aget (Fig. 3.1a) only the end of July heat wave is seen, due to a longer lasting snow cover.

GST recorded in steep bedrock locations exhibit a different behaviour compared to the values measured at sites in loose debris (Fig 3.1 g-h). The temperatures closely follow the evolution of air temperature in steep rock due to the absence of an insulating snow cover. The impact of the end of June heat wave is more clearly visible here because snow was still present at most of the debris sites. At the end of June 2019, GST at Murtèl-Corvatsch reached values never registered before, since the start of the measurements in 2002.

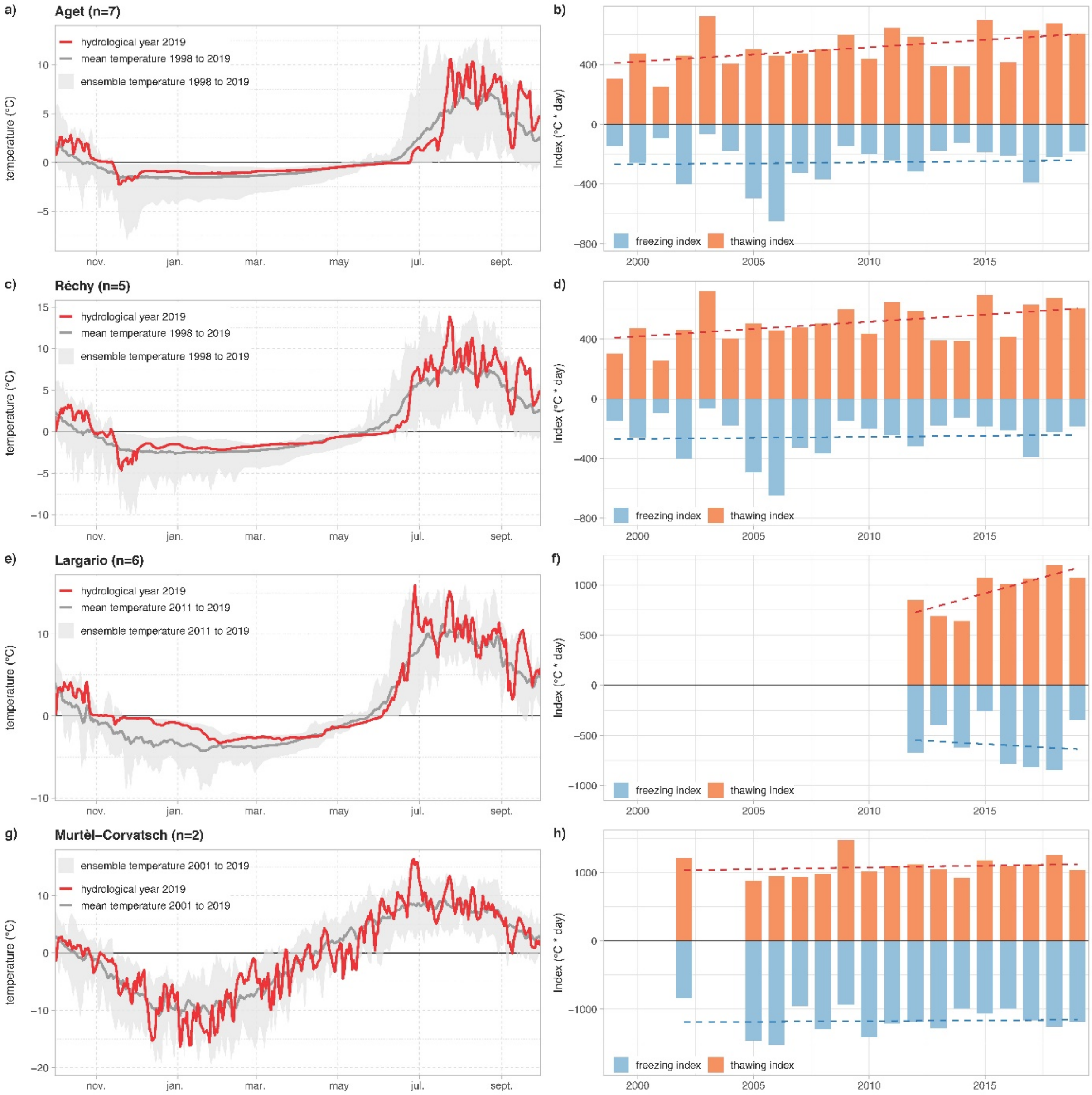

Figure 3.1: Seasonal pattern of ground surface temperature (left) and Ground Freezing and Thawing Indices (right) at selected sites in loose debris material: the Aget push moraine, Lower Valais (a-b), the Réchy-Becs de Bosson rock glacier, Lower Valais (c-d) and the Largario rock glacier, Southern Alps (e-f) as well as in near-vertical bedrock at the Murtèl-Corvatsch site, Engadine (g-h). The number in brackets (left panel) denotes the number locations used to calculate a site mean. The dotted lines (right panel) indicate the linear trend since the beginning of the measurements.

The long-term evolution of the mean annual ground surface temperature (MAGST, Fig. 3.2) shows that there has been a small increase of the near-surface temperatures since 2008. Maxima were reached in the very warm years 2015 and 2018 (cf. Fig. 2.1). Locations where a significant winter snow cover typically develops also underwent substantial cooling at the ground surface in 2017 due to the extremely snow-poor winter 2016/2017 (PERMOS 2019).

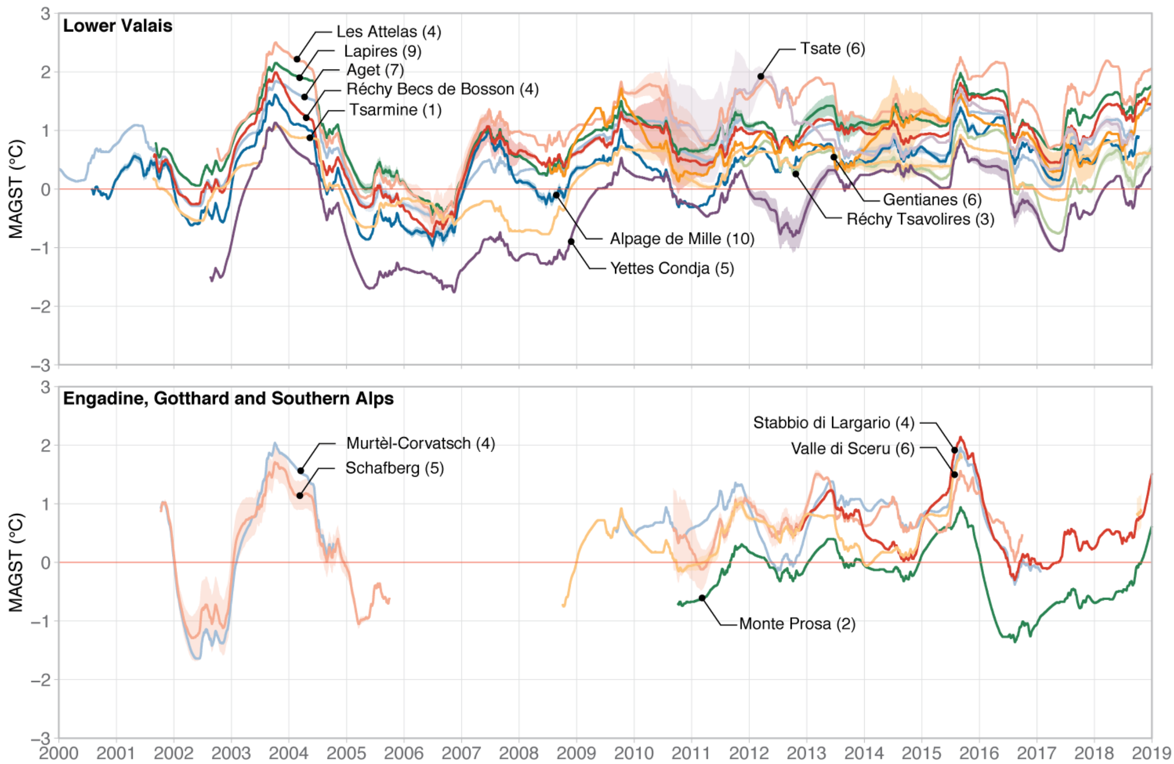

Figure 3.2: Smoothed Mean Annual Ground Surface Temperature (MAGST) in different regions in the Swiss Alps: Valais (top panel), Engadine (Murtèl-Corvatsch and Schafberg, lower panel), and Gotthard and Southern Alps (Monte Prosa, Largario and Sceru, lower panel). The number of loggers considered at each site is indicated in brackets in the legend. The shaded areas illustrate the estimated uncertainty range resulting from gap-filling.

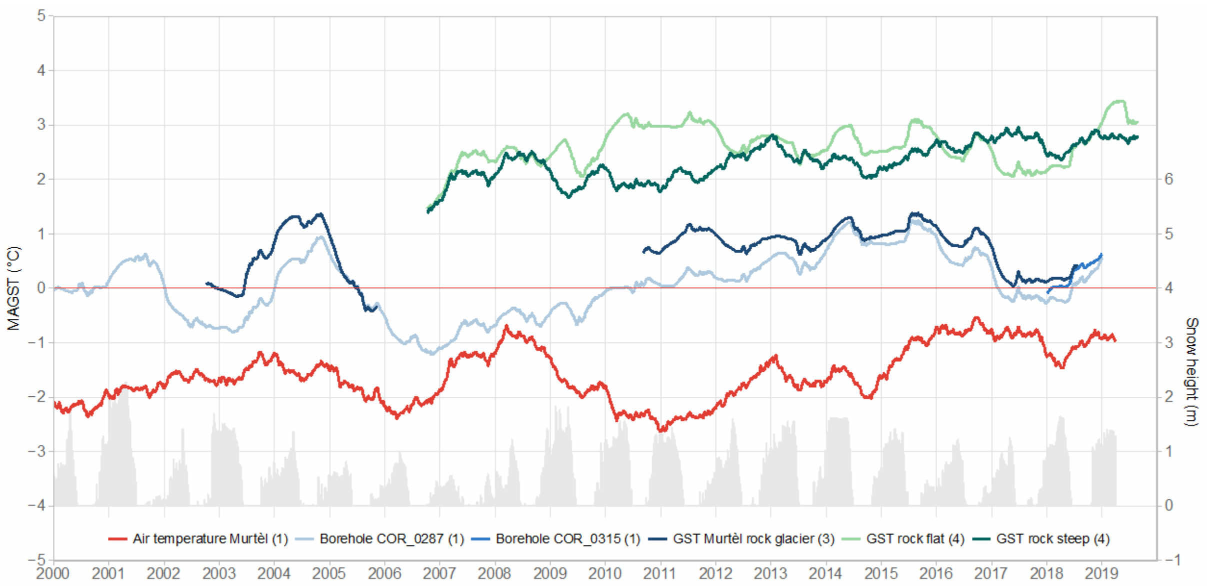

Figure 3.3: Two-annual running means of GST at locations with different surface characteristics at the site Murtèl-Corvatsch compared to air-temperature and snow-height measured at the borehole site. The mean GST of several loggers was calculated for the mean of different groups: in coarse blocks (GST Murtèl-Corvatsch rock glacier), flat bedrock (GST rock flat) and steep bedrock (GST rock steep). In addition, the uppermost thermistors of boreholes COR_0287 (0.55 m) and the new borehole COR_0315 (0.25 m) are shown. The snow height is displayed in grey at the bottom.

The long-term evolution of MAGST in steep bedrock (Fig. 3.3) also shows an increasing trend. Here, the evolution is mostly driven by the air temperature and the cooling effect resulting from the snow-poor winters 2015/2016 and 2016/2017 is not present.

The observed warming GST trend results from the warmest decade (2010–2019) ever measured in Switzerland. At the large majority of the PERMOS sites, MAGST remained above 0°C throughout the entire decade, illustrating the imbalance between the permafrost conditions and the current climatic setting.

3.2 Active layer thickness

The ALT is determined based on linear interpolation of temperatures measured in boreholes by the lowest sensor in the active layer and the uppermost sensor in the permafrost. The warm near-surface conditions in summer 2018 and 2019 led to new record ALT in 2019 at several borehole sites, for example at Murtèl-Corvatsch (GR), Lapires (VS), Les Attelas (VS) or Stockhorn (VS, Fig. 3.4). At the other sites, the ALT in 2019 was in the range of the 2018 values.

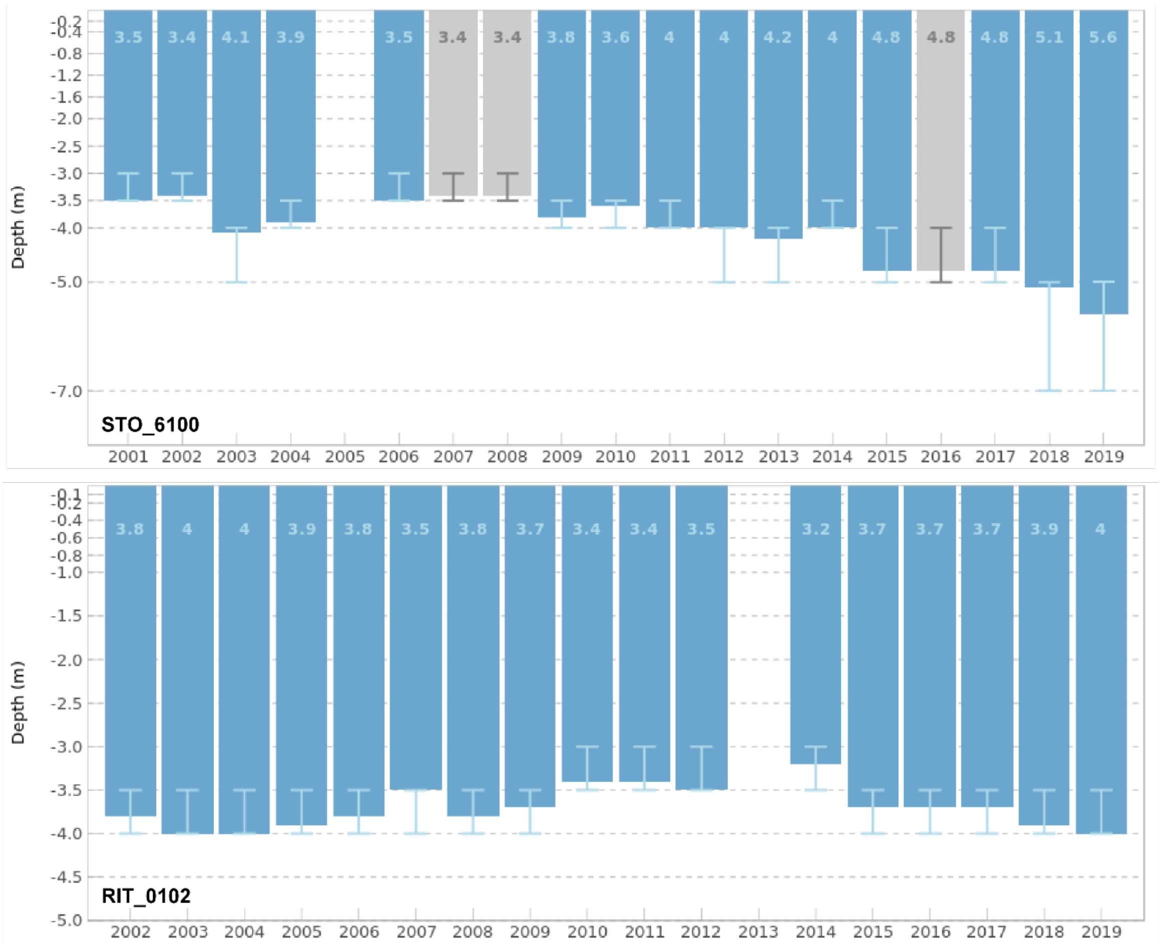

Figure 3.4: Maximum active layer thickness (ALT) derived from the temperature data for the Stockhorn plateau (borehole STO_6000, upper panel) and the Ritigraben rock glacier (borehole RIT_0102, lower panel). The exact ALT values are indicated and the uncertainty bars represent the thermistors used for the calculation. The grey bars and values represent uncertain data quality.

3.3 Permafrost temperatures

At sites influenced by an insulating winter snow cover (i.e. debris slopes and rock glaciers), the permafrost temperatures measured at 20 m depth increased again in 2018/2019 after a temporary cooling period of two years (Fig. 3.5). At 10 m depth, the temperatures almost regained the 2015/2016 record levels reached before the temporary cooling period.

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). At sites with permafrost temperatures close to 0°C (e.g. Schilthorn, Lapires or Schafberg), no substantial temperature increase can be observed due to effects of latent heat during phase change (see Fig. 4.2).

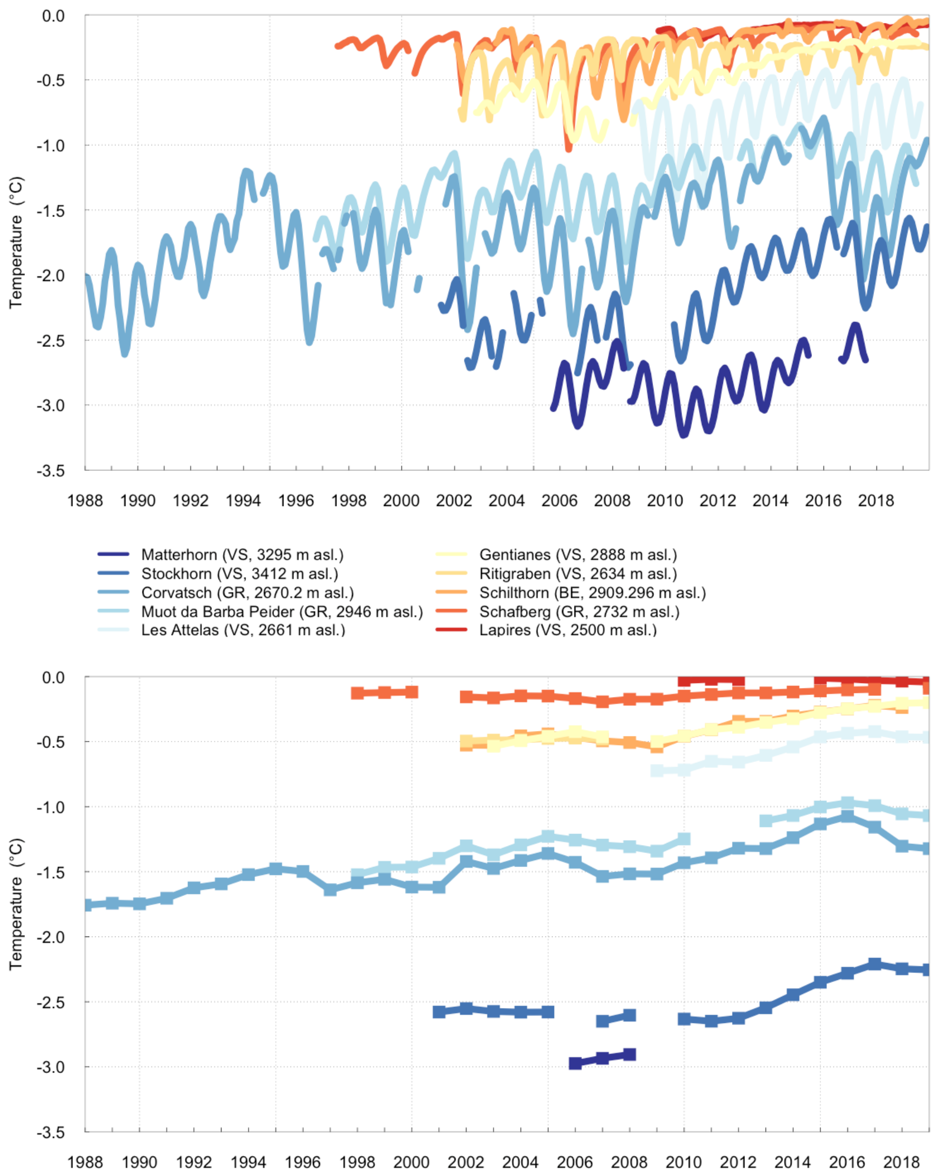

Figure 3.5: Ground temperatures measured in selected boreholes at ca. 10 m depth (monthly means, top) and ca. 20 m depth (means of the hydrological year, bottom). The actual depths are given in brackets in the legend.

4 Electrical resistivities

Electrical resistivity tomography (ERT) are an important complement to ground temperature measurements, particularly at sites where the permafrost temperatures are close to 0 °C. Here, warming at the surface does not result in a significant increase of ground temperatures until the ground has reached positive temperatures because of the latent heat required for the melt of the ground ice. Changes in electrical resistivity of frozen and unfrozen materials can be observed using repeated measurements (Fig. 4.1), and are related to the changes in ground ice and liquid water content: decreasing electrical resistivities indicate an increase of the ratio between liquid water and ice content. In general, such an increased resistivity indicates a decrease in the overall ice content. Conversely, increasing electrical resistivities indicate a decrease of the ratio and an increase of the ice content.

Figure 4.2 shows the evolution of the electrical resistivity within the permafrost layer at five sites from 1999 until 2019. The general decreasing trend reported in the past five years (PERMOS, 2019) continued in 2019. All sites except Murtèl-Corvatsch exhibited a resistivity decrease compared to 2018, with a maximum decrease observed at Stockhorn. The latter is consistent with the borehole temperatures, which were the highest ever measured at 4, 5 and 7 m depth (i.e. the depth of the selected permafrost zone shown in Figures 4.1 and 4.2), and with a record ALT in autumn 2019 (Chapter 3). At Murtèl-Corvatsch, a slight increase in resistivity was observed in 2019.

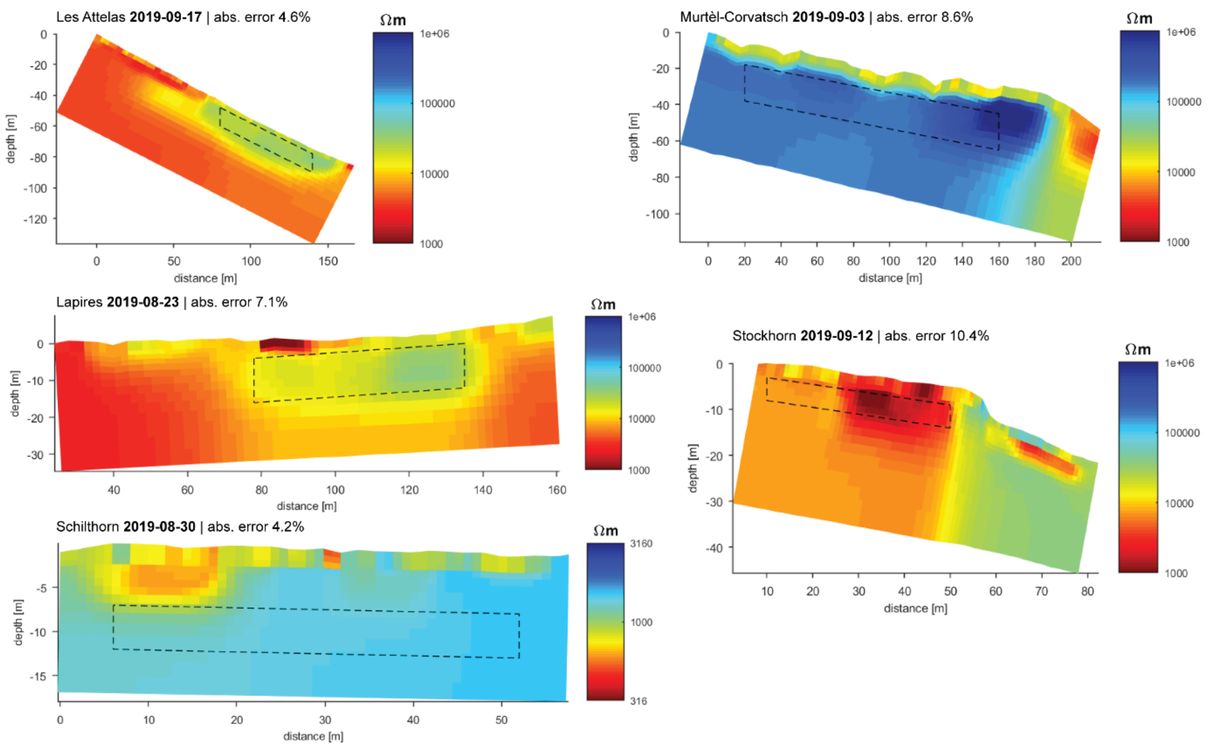

Figure 4.1: ERT-Tomograms showing the resistivity distribution in 2019 at the five PERMOS ERT profiles (note the different resistivity scale for Schilthorn). The representative zones used for the time series in Fig. 4.2 are indicated with dashed boxes.

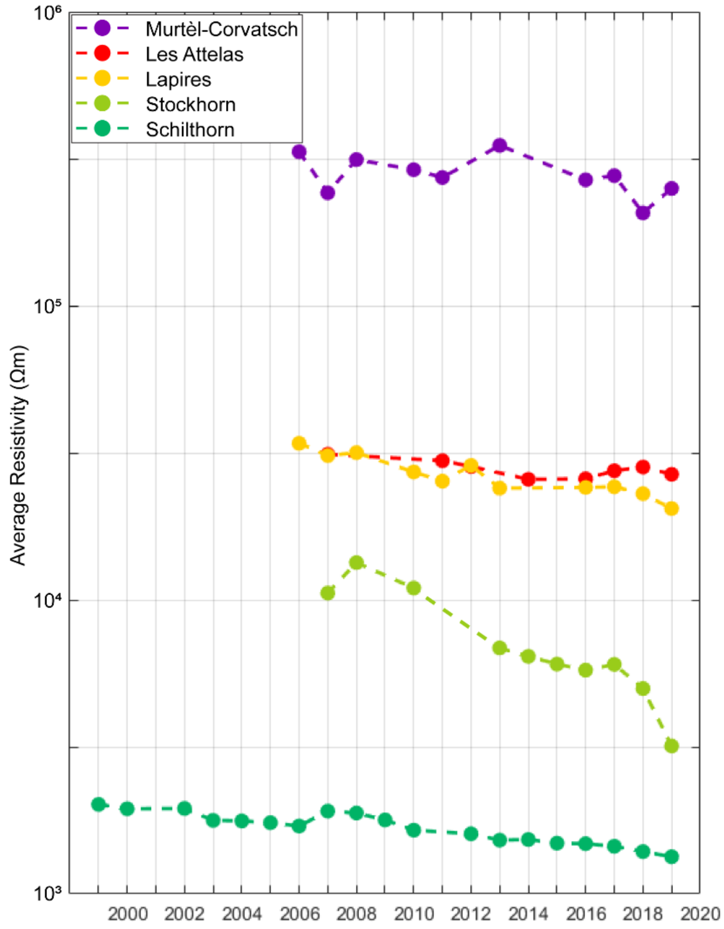

Figure 4.2: Average electrical resistivities of the permafrost zone (see Fig. 4.1) at the end of summer (August–September) for different sites.

No trend reversal (i.e. no increase of electrical resistivity) was observed in the end-of-summer measurement from 2017 to 2019, which is contrasting the observed temporary decrease in permafrost temperatures (Chapter 3). A slight resistivity increase can be seen after the winter 2017 in the two talus slopes (Lapires and Les Attelas), which are more sensitive to snow-poor winters due to conductive cooling and reinforced air circulation. The absence of trend reversal in the permafrost resistivity indicates that there was no ice aggradation during this period and that the snow-poor winters only had a thermal effect. Overall, the continued warm climate conditions of the past two decades yielded a clear trend of decreasing resistivities, which is indicative for permafrost degradation, i.e. for a loss of ground ice.

5 Kinematics

The kinematics of creeping permafrost landforms, such as rock glaciers, reveal indirect information about the ground thermal conditions and are integrated into the PERMOS strategy since 2007. Inter-annual changes in the creep behaviour were shown to mainly follow an exponential relation with air and ground surface temperature (i.e. warming air/ground temperature lead to an increase of velocity, and conversely for cooling temperatures). Terrestrial geodetic surveys (TGS) are performed once a year at the end of the summer (August-September) to measure the position of selected boulders spatially distributed on rock glaciers. Repeating these measurements at the same period every year allows to assess the annual displacement and thus the velocity of rock glaciers.

5.1 Annual terrestrial geodetic surveys

The observation year 2018/2019 was characterized by a general velocity increase at all sites except for Murtèl-Corvatsch and Lapires. Compared to 2017/2018, the mean of all sites increased by +21% (Fig. 5.1), with the largest velocity increase observed in the Gotthard and Southern Alps region (+46% compared to 2017/2018 for the entire region, and up to +67% at single sites). This is consistent with the limited winter cooling recorded at these sites. A general trend of increasing velocity can be concluded for the observation year, despite strong site-specific and inter-annual variations.

This follows an intermediate year of trend recovery marked by very different regional signals in 2017/2018 (Fig. 5.2). The trend of increasing velocity observed since the start of the measurements about 15 years ago continued. The velocities measured in 2018/2019 reached comparable values as in 2013/2014 at all sites. So far, record values were reached in 2014/2015 at most of the sites.

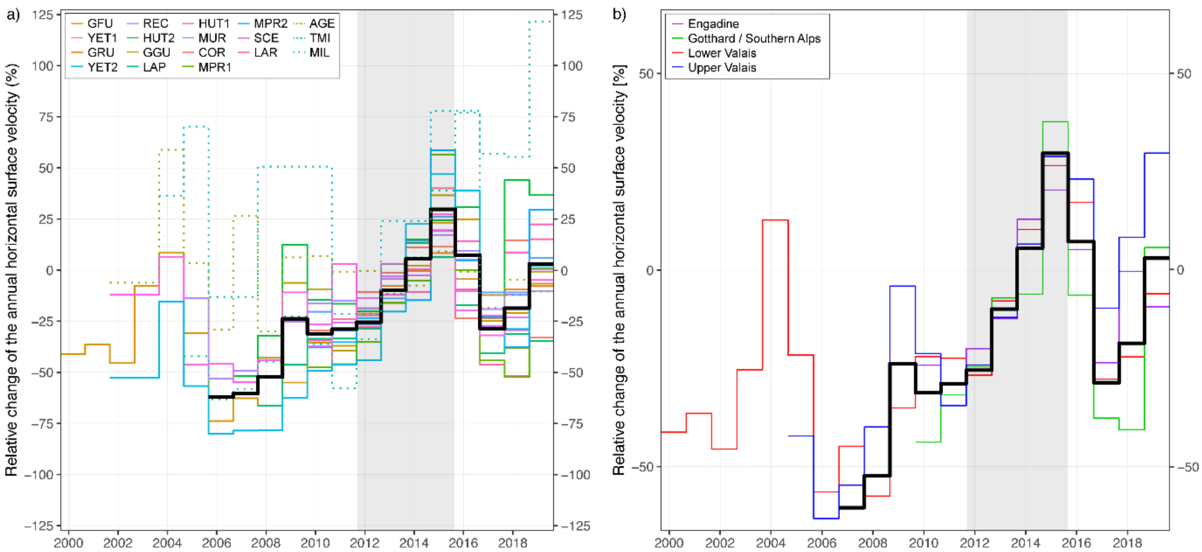

Figure 5.1: Mean annual horizontal surface velocity derived from terrestrial geodetic surveys relative to the reference period 2012–2015 (grey area). Dotted lines represent the rock glaciers with atypical evolution and the black line represents the average of the Swiss Alps (excluding the two atypical rock glaciers). Left: all 17 monitored rock glacier lobes (for site abbreviations see Table A.1). Right: average velocity for the four topo-climatic regions.

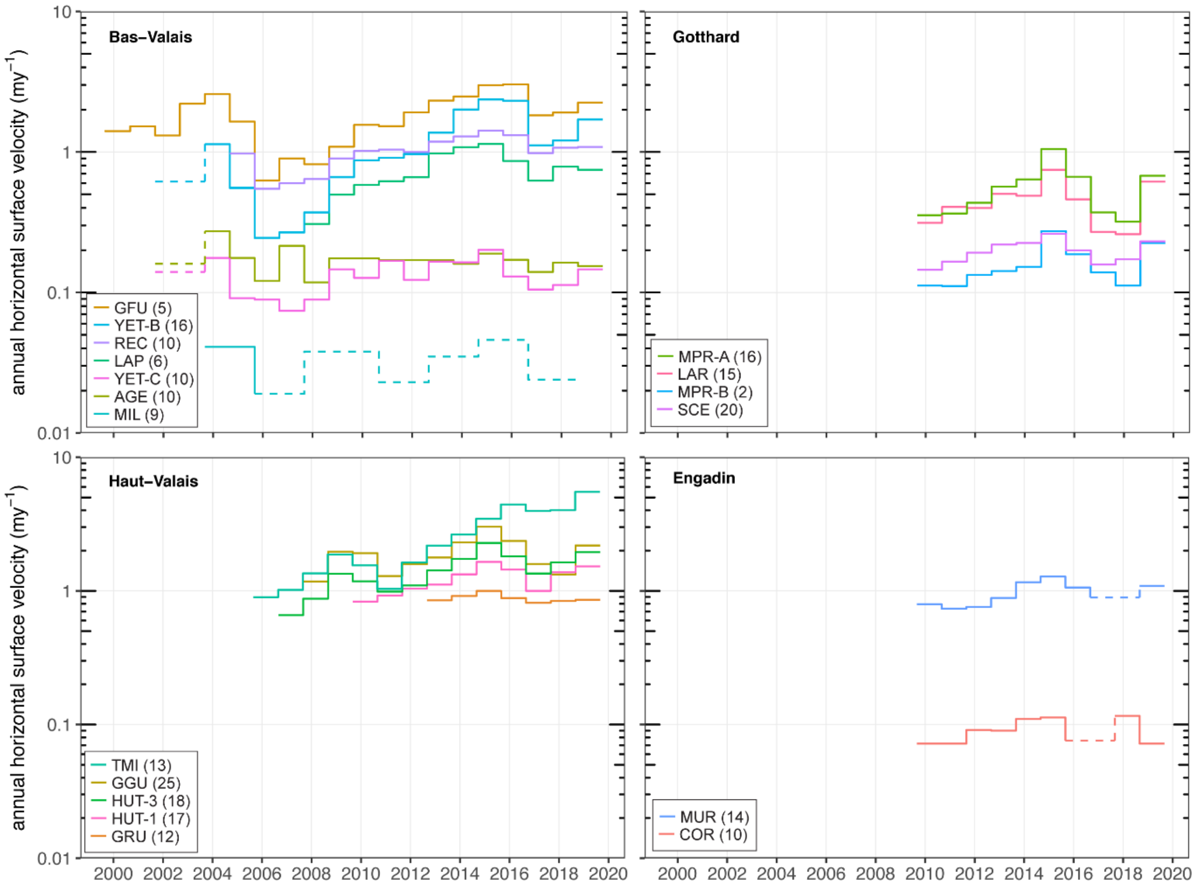

Figure 5.2: Velocity pattern of 18 rock glacier lobes in the Swiss Alps divided into four topo-climatic regions. The number of reference points for each site is indicated in brackets and the dashed lines represent velocities measured over two years. The abbreviations for the site names can be found in Table A.1.

5.2 Permanent GNSS

Permanent GNSS complement the annual TGS surveys to capture the short-term (daily), seasonal and intra-annual variations in rock glacier kinematics. The higher temporal resolution provided by permanent GNSS implies that displacements measured are much smaller than the annual values. The reliability and significance of the small variations (typically +/-0.1–0.2 my^{-1}) are difficult to assess and have to be interpreted with caution. They depend on a wide range of factors, and may not be representative of the rock glacier motion (e.g., snow pressure on the mast in winter, stability and anchorage of the boulder in the terrain).

Figure 5.3 shows the seasonal evolution of creep velocities for the two rock glaciers Réchy (blue line) and Monte Prosa (green line). The positions are averaged using a 14-day moving window and the displacements are then calculated over a 14-days period. A typical seasonal velocity pattern with decreasing velocities throughout the winter (minima reached end of April) is visible at Réchy, followed by a strong acceleration at the beginning of summer (during snow melt) and peak velocities in September/October. The end of summer acceleration was more pronounced in 2018/2019 than in the previous years, likely due to the June 2019 heat wave. This is also visible at Monte Prosa.

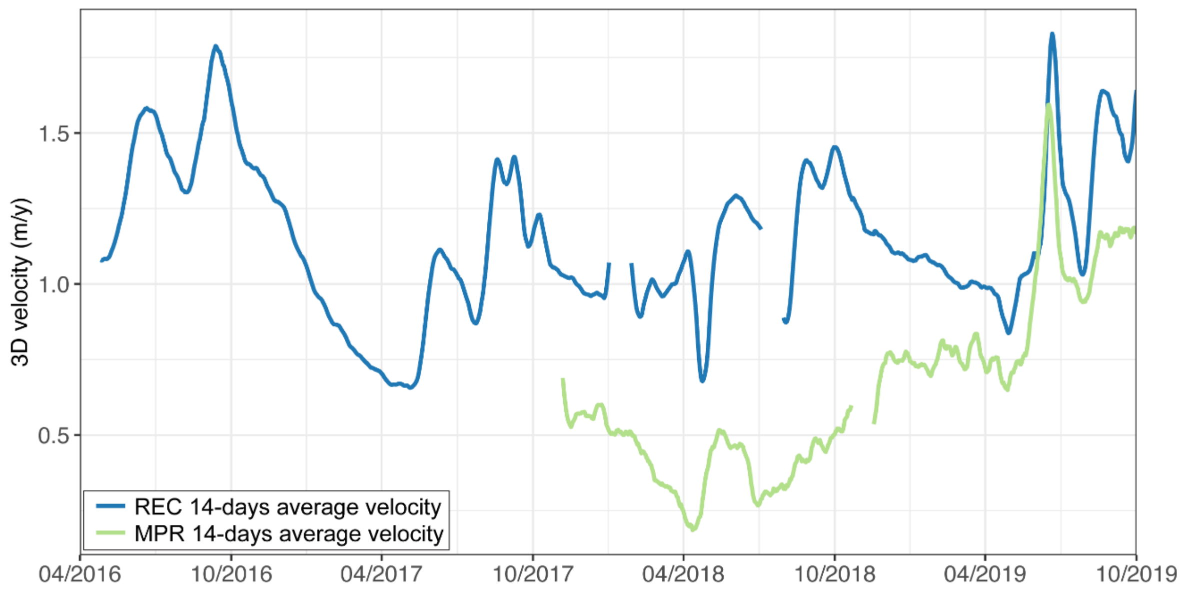

Figure 5.3: Evolution of the seasonal creep velocity at the Réchy (blue) and Monte Prosa (green) rock glaciers. The velocities are computed over a 14-day period using daily positions.

The two sites mainly differ in their winter conditions. The absence of a velocity decrease at Monte Prosa during winter 2019 is consistent with warm GST conditions documented south of the Alps and in the Gotthard area (see also Fig. 3.1 and 5.2). Conversely, GST close to the long-term average at Réchy (i.e. winter cooling occurred, see Fig. 3.1) resulted in a velocity decrease.

5.3 Rock falls in permafrost areas

During the observation year, one major rock fall event starting from permafrost area occurred in the Swiss Alps. A rock fall with a volume of about 300’000 cubic metres detached on Monday 19 March 2019 from the southwest ridge of the Flüela Wisshorn (3085 m asl., Davos GR). The rock fall triggered a large snow avalanche, which almost reached the closed Flüela Pass road. The coarse blocks of the rock fall were deposited in the high valley below the summit. The starting zone is exposed north-west at 3000 m asl. and is very likely within the permafrost zone. The permafrost in steep ice-poor rock walls and ridges has warmed significantly in recent years. To which extent this has played a major role to trigger this event – in addition to the unstable geological structure left behind by the last glaciation – cannot yet be assessed. Larger rock fall events (> 100’000 m^3) from permafrost regions can occur throughout the year because the annual temperature fluctuations at the surface arrive at depth with a delay of several months or are no longer measurable at all,. Such events can reach sizes of tens of thousands of cubic metres. Smaller events, instead, accumulate during the warm seasons, as shown by the rock fall inventory of PERMOS/SLF.

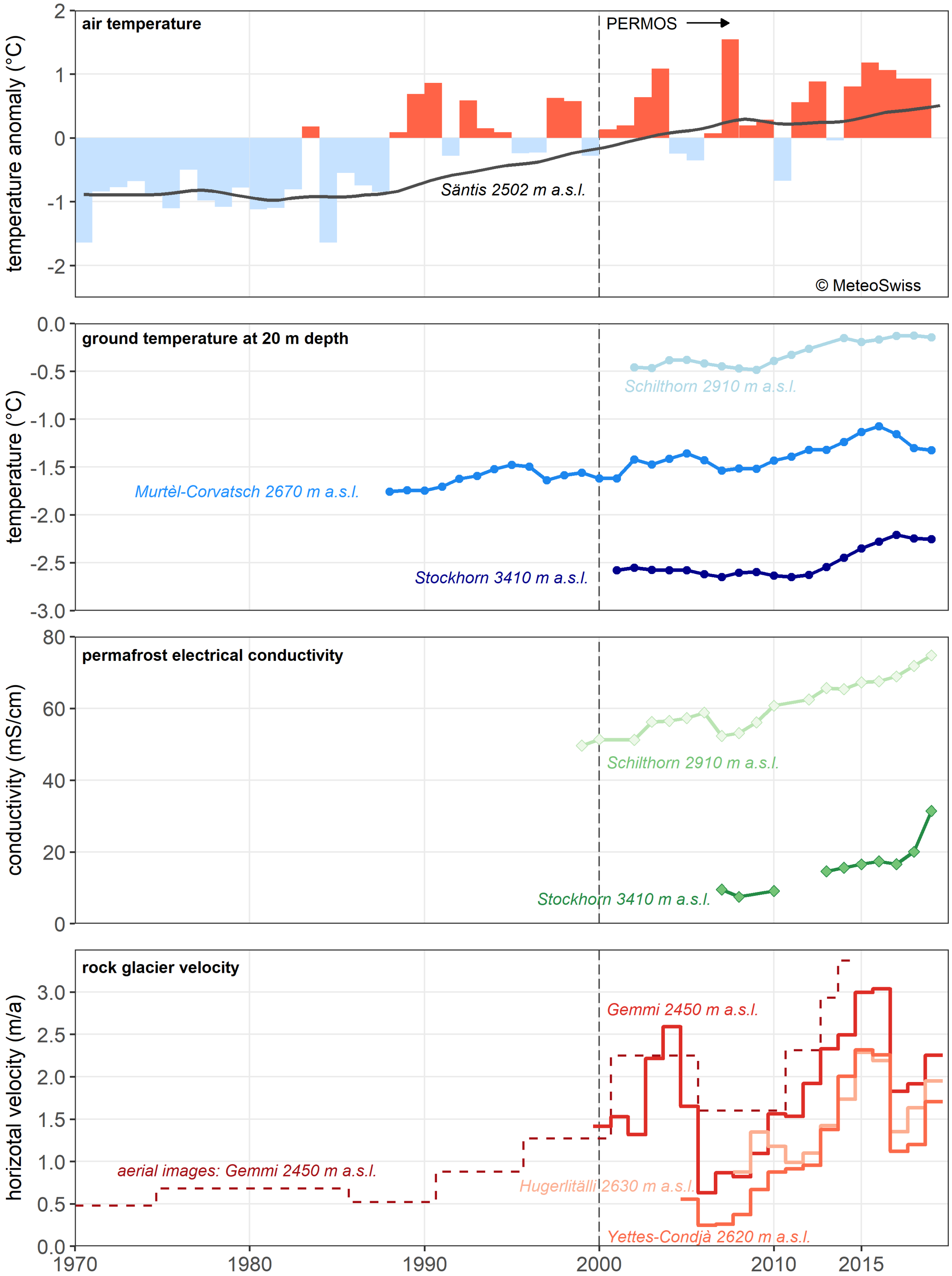

Figure 6.1: Evolution of the three PERMOS observation elements: annual mean temperatures at around 20 m depth (b), permafrost electrical conductivity (c), and rock glacier creep velocity (d). The data are compared to long-term air temperature observations (a, data source: MeteoSwiss).

6 Key messages

6.1 Hydrological year 2018/2019

- Different snow conditions and air temperatures characterized winter 2018/2019 across regions, leading to different temperature and velocity signals.
- The cold and humid spring (April–May 2019) resulted in a long-lasting snow cover, which melted quickly after the heat wave end of June. In combination with the relatively warm winter, this prevented new temperature records in summer 2019 although GST were above average throughout the hydrological year.
- Maximum ALTs reached record values in 2018 and 2019.
- At sites influenced by an insulating snow cover (i.e. talus slopes and rock glaciers), the temperatures at 20 m depth have increase again after a temporary pause in 2016–2017 to the range of the 2014/2015 values.
- The decreasing trend of electrical resistivities continued in 2019. The values measured end of August were the lowest ever at Schilthorn, Stockhorn and Lapires, indicating an increasing water-to-ice ratio. These observations are consistent with the deepest ALT ever measured at Lapires and Stockhorn.

⇨ Although strong regional differences were observed due to the snow conditions, all three observation elements showed consistent signs of permafrost warming and degradation in 2018/2019 and the long-term trends of high surface and ground temperatures, thick ALTs, increasing rock glacier velocities, and decreasing electrical resistivities continue.

6.2 PERMOS 20th anniversary

- PERMOS is celebrating 20 years of coordinated permafrost monitoring in the Swiss Alps in the year 2020. PERMOS is the world's first national network set up for long-term monitoring of mountain permafrost and an early component of the Global Terrestrial Network for Permafrost GTN-P. PERMOS is considered a role model for national operational permafrost observations.
- PERMOS archives the largest and most comprehensive data collection on mountain permafrost worldwide, including the longest uninterrupted temperature time series of Murtèl-Corvatsch, which now covers 33 years. PERMOS progressively developed and implemented a standardized data management system in the past decade, which includes systematic data and meta-data archiving, automatic processing routines, and open online data access.
- The air temperatures during the past two decades have been the highest in Switzerland since the start of the measurements in 1864. There was a continuous increase of air temperatures, and the five warmest years were all recorded during the past decade.
- The mean annual ground surface temperature remained above 0°C throughout the past decade at most PERMOS sites, illustrating the imbalance between the permafrost conditions at depth and warming conditions in the atmosphere and at the surface.
- Ground temperatures near the surface, at 10 m depth, and at 20 m depth, all showed a general and consistent warming trend over the past 20 years (e.g. +0.5°C at 20 m and +1°C at 10 m at Murtèl-Corvatsch). Extraordinary snow poor conditions led to a temporary interruption of the warming trend after winter 2016/2017 down to large depths. Permafrost temperatures in steep bedrock slopes, where no insulating snow cover accumulates during winter, continuously increased without interruption.

- The active layer thickness significantly increased at all PERMOS sites, at some sites even by several metres. The absolute increase depends on site characteristics, particularly ground ice content and non-conductive heat transport.
- Since the start of the measurements in 2005, the electrical resistivities within the permafrost consistently decreased at all sites. This indicates an increased ratio between liquid water and ice, or a loss of ground ice. Electrical resistivity tomography (ERT) has proven to be a robust indicator of the changes in permafrost conditions where temperature are close to the ice melting point. ERT exhibits less inter-annual variability than temperature measurements or creep velocities, thus indicating persistent permafrost degradation.
- Increasing rock glacier velocity can be observed at all sites, in line with the increase in ground temperatures and water contents. This is indicative of warming permafrost. Creep velocities over the past decades show a similar evolution despite strong site-specific and inter-annual variations.

⇨ The three main PERMOS observation elements – ground temperatures, changes in ground ice content, and creep velocities – consistently show permafrost warming and degradation over the past 20 years (Fig. 6.1). The trend increased in the past decade and was temporarily interrupted by one (or two in specific regions) snow poor winter. From 2000 to 2020, the permafrost in the Swiss Alps was characterized by warming near-surface and ground temperatures, deepening ALT, increasing rock glacier velocities, and decreasing ground ice contents.

⇨ The most important factors influencing the evolution of permafrost temperatures are the climatic conditions, the temperature range of the permafrost, the ground ice content, and the snow cover. The warming rates are highest in cold bedrock containing only very small amounts of ground ice and decrease to nearly zero for warm permafrost in ice-rich rock glaciers and debris slopes. Changes in the timing and duration of the snow cover can accelerate on interrupt warming trends.

⇨ Extreme events, such as the hot year 2003 or the snow-poor winter 2016/2017, can temporarily strongly affect the permafrost conditions – even at large depths of 20 m and more. Overall permafrost degradation trends, however, result from constantly warm conditions over prolonged periods.

7 References

MeteoSwiss 2020. Bulletin climatologique année 2019. Genève.

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, doi.org/10.13093/permos-rep-2019-16-19.

Zweifel, B., Lucas, C., Hafner, F., Marty, C. and Stucki, T. 2019. Schnee und Lawinen in den Schweizer Alpen. Hydrologisches Jahr 2018/19. WSL Ber. 86: 134 S.

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., … Lantuit, H. (2019). Permafrost is warming at a global scale. Nature Communications, 10(1), 264. https://doi.org/10.1038/s41467-018-08240-4

Appendix

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		

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