Permafrost in Switzerland

2008/2009 and 2009/2010

Glaciological Report (Permafrost) No. 10/11

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Permafrost Monitoring Switzerland

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Becs de Bosson (3149 m a.s.l.) at the PERMOS Reference Site Réchy. Here, rock surface temperatures are measured in the steep rocks. Photo: Reynald Delaloye.

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Published Reports

The PERMOS concept and annex were approved by the permafrost coordination group on November 18, 1999 and by the Cryospheric Commission (Expertenkommission Kryosphäre EKK; former Glaciological Commission) on January 14, 2000 and were published in 2000. Annual reports on «Permafrost in Switzerland» started in 1999. The reports listed below are also available for download on the PERMOS website: http://www.permos.ch

Reporting Period	*Report No.*	*Published*
1999/2000	1	2001
2000/2001 and 2001/2002	2/3	2004
2002/2003 and 2003/2004	4/5	2007
2004/2005 and 2005/2006	6/7	2009
2006/2007 and 2007/2008	8/9	2010
2008/2009 and 2009/2010	10/11	2013

Preface

On 3. July 2012 some 25 master students of the University of Zurich practiced geophysical methods they had learned earlier in theory during the lectures in the Upper Engadin: refraction seismics, DC resistivity soundings, and ground penetrating radar around the glacier tongue of Morteratsch glacier. The day after, the group did an excursion to the nearby Murtèl-Corvatsch, similarly as to the day before, when the excursion Muragl-Schafberg-Languard was on the program. Exactly 25 years earlier, on 3. July 1987, the first permafrost temperature measurements were taken in the core drilling through the Murtèl rock glacier. At the time, I was the diploma student responsible for the temperature readings. My thesis was part of the ETH research project «Permafrost Core Drilling» led by my supervisor Wilfried Haeberli. Two amongst other goals of the project were (a) educated students on various levels, and (b) set up the installation for long-term monitoring.

This project was an important milestone, which since has not only triggered many new ideas and research projects, but also friendships. In addition, it is the nucleus of the Swiss Permafrost Monitoring Network PERMOS, the longest time series of mountain permafrost measurements and, hence, role model for many permafrost temperature surveys around the globe. The PACE (Permafrost and Climate in Europe) project would not have been launched without the experience of the Murtèl project. In turn, with PACE a European permafrost monitoring network has been established, which allowed to educate students and up to date still provides status of the permafrost between Svalbard and Italy. Murtèl rock glacier has also served as pilot for testing new methods – e.g., seismic tomography, DC resistivity tomography, GPR: subsurface and surface characteristics were known better than at any other place.

The concept for PERMOS elaborated by the Permafrost Coordination Group of the Swiss Academy of Sciences (SCNAT) was approved by the Glaciological Commission for a pilot phase from 2000–2003. The Federal Office of Forest and Landscape and the Federal Office of Water and Geology – both later merged to the Federal Office for the Environment (FOEN) – decided to support PERMOS as well. The pilot phase was prolonged until 2006. Meanwhile, MeteoSwiss has become a PERMOS partner. Finally, a cooperation contract for 2007–2010 was signed by SCNAT, FOEN and MeteoSwiss. In 2008, the Federal Council approved the GCOS-request to ensure funding for networks monitoring essential climate variables, where PERMOS was one part.

Since the beginning, it was actually the Swiss permafrost research community that implemented PERMOS and made it a success. Many scientists, students and technicians of six research institutions invested more than just time and money for the drilling, the monitoring of loggers, and the installation of a lot of other equipment. The secret behind the success of PERMOS is the passion and enthusiasm of everyone contributing to this unique network. Many thanks to all! The two excursions mentioned above became a classic: Within the past 25 years over a thousand scientists, teachers, students, tourists, and engineers have followed the explanations of a field guide.

With the present report I pass on the lead and responsibility of PERMOS to Jeannette Nötzli. For the past four years we have been preparing for this change. I wish Jeannette and PERMOS all the best and as many interested and constructive helpers as I was able to count on from the very beginning.

October 2012 , Daniel Vonder Mühll

Summary

This report on permafrost in the Swiss Alps covers the two hydrological years 2008/2009 and 2009/2010. It is the second report of the implementation phase 2007–2010 of the Swiss Permafrost Monitoring Network PERMOS and the 5th of its kind. It completes the first 10 years of official PERMOS operation, which started with a first pilot phase in the year 2000. The PERMOS observation strategy today follows a landform-based approach and builds on three observation elements that complement each other in order to deliver a comprehensive picture of permafrost state and changes in the Swiss Alps. The observation elements include ground temperatures, changes in ice content and permafrost creep velocities and the four main landforms distinguished are rock walls, crests, talus slopes, and rock glaciers.

The meteorological conditions in 2008/2009 were characterised by an early and long winter, followed by a hot spring, a changeable summer and an extremely warm autumn in 2009. As a result of these conditions, the snow cover has melted early in mid June despite new snow depth records at several stations. Winter 2009/2010 was relatively cold and the following spring, summer, and autumn 2010 were all characterised by variable weather and normal temperatures. Despite generally below average snow amounts, the meld out only occurred end of June. 2010 was 0.2 °C warmer than the long-term mean, in the past 22 years however only in 1996 temperatures were lower.

Near-surface temperatures measured during the reporting period reflect the atmospheric conditions during the two years. Especially the warm late summer 2009 led to high ground surface temperatures in the range of the 2003 extreme values. In the moderate summer 2010 temperature conditions were cooler again. In general, surface temperatures were higher than during the previous reporting period. After a 5-year period with more or less stable values the active layers were significantly deeper for both reporting years as a result of the warm summer conditions, especially in 2009. Similarly, the ground temperatures at about 10 m depth have been above the average of the previous years and particularly minimum ground temperatures at snow-rich sites were at record values for both reporting years. The only site with a clear signal that indicates an evolution in the resistivity measurements in the period 2008–2010 is Schilthorn with exceptionally low values. This is attributed to a cumulative effect of the two rather warm years 2009 and 2010, which is also visible in the borehole temperatures and active layer depths. Active layer depths increased in 2009 and 2010 compared to previous years at all other ERT monitoring sites, except for the Flüela site, where slightly lower resistivities were observed compared to previous years. After the extraordinarily high flow velocities of rock glaciers in 2003 and 2004, the velocities dropped until 2006. Since 2007 most of the sites show a small increase. While the relative changes in horizontal velocities show large variations between 2001 and 2005, the changes have been much smaller in recent years. Finally, nine rock fall events with a volume of at least 1000 m^3 and at elevations between 2700 and more than 4000 m a.s.l. have been documented in the permafrost areas of the Swiss Alps during the reporting period.

In summary, all three observation elements indicate very warm permafrost conditions for the reporting period compared to the previous five years since the record summer of 2003. This results especially from the very warm year 2009 with a hot autumn and following the early snow fall in October.

Zusammenfassung

Der vorliegende Bericht dokumentiert den Permafrost in den Schweizer Alpen in den beiden hydrologischen Jahren 2008/2009 und 2009/2010. Dies ist der zweite Bericht der Implementationsphase 2007–2010 des Schweizer Permafrostbeoachtungsnetzwerks PERMOS und der fünfte seiner Art. Der Bericht komplettiert die ersten 10 Jahre des offiziellen Betriebs von PERMOS, der in Jahr 2000 mit einer ersten Pilotphase startete. Die Beobachtungsstrategie von PERMOS verfolgt heute einen Landform-basierten Ansatz und setzt auf drei Beobachtungselemente, die sich gegenseitig ergänzen und zusammen ein umfassendes Bild des Zustands und der Veränderungen des Permafrosts in den Schweizer Alpen abgeben. Die Beobachtungselemente sind Oberflächen- und Untergrundtemperaturen, Veränderungen des Eisgehalts und Permafrostkriechgeschwindigkeiten. Die vier hauptsächlichen untersuchten Landformen sind Felswände, Grate, Schutthalden und Blockgletscher.

Die meteorologischen Verhältnisse 2008/2009 waren geprägt von einem frühen und langen Winter, gefolgt von einem heissen Frühling, einem wechselhaften Sommer und einem aussergewöhnlich warmen Herbst 2009. Diese Verhältnisse führten trotz neuer Schneehöhen-Rekordwerte an verschiedenen Stationen zu einer Schneeschmelze Mitte Juni. Der Winter 2009/2010 war relativ kalt und in den folgenden Sommer-, Frühlings- und Herbstmonaten herrschten variable Wetterbedingungen und normale Temperaturen vor. Die Schneeschmelze erfolgte Ende Juni, trotz der generell unterdurchschnittlichen Schneehöhen. Das Jahr 2010 war 0.2 °C wärmer als im langjährigen Mittel, jedoch waren die Temperaturen in den vergangenen 22 Jahren nur 1996 tiefer.

Die oberflächennahen Temperaturmessungen widerspiegeln die atmosphärischen Verhältnisse während der zweijährigen Berichtsperiode. Besonders der warme Spätsommer 2009 führte zu hohen Oberflächentemperaturen im Bereich der Rekordwerte von 2003. Im milden Sommer 2010 waren die Werte wieder etwas tiefer, gesamthaft jedoch waren die Oberflächentemperaturen höher als in der vorhergehenden Berichtsperiode. Die Auftauschichten in der Berichtsperiode waren nach fünf Jahren mit mehr oder weniger konstanten Werten aufgrund der warmen Sommer deutlich tiefer, insbesondere im Jahr 2009. Ebenso waren die Untergrundtemperaturen in einer Tiefe von ca. 10 m höher als der Durchschnitt der letzten Jahre, besonders die Minimumtemperaturen an schneereichen Standorten zeigten Rekordwerte für beide Jahre. Bei den Widerstandsmessungen war das Schilthorn der einzige Standort mit einer deutlichen Entwicklung von 2008–2010 und extrem tiefen Werten. Dies ist vermutlich das kumulierte Resultat der beiden eher warmen Jahre 2009 und 2010, was auch in den Auftautiefen und Untergrundtemperaturen sichtbar ist. An allen anderen Standorten zeigen die Widerstandsmessungen zunehmende Auftautiefen mit Ausnahme des Standortes Flüela, wo leicht tiefere Widerstandswerte gemessen wurden als in den vorhergehenden Jahren. Die Blockgletschergeschwindigkeiten sind nach den hohen Werten in 2003 und 2004 bis 2006 gesunken und seit 2007 haben sie an den meisten Standorten wieder leicht zugenommen. Während die relativen Änderungen der horizontalen Geschwindigkeiten grosse Unterschiede zeigen zwischen 2001 und 2005, waren die Änderungen in den letzten Jahren deutlich kleiner. Die Dokumentation der Felsstürze aus Permafrostgebieten in der Schweizer Alpen wurden um neun Ereignisse in der Berichtsperiode mit einerm Volumen von mindestens 1000 m^3 und in einer Höhe von 2700 bis über 4000 m ü.M. ergänzt.

Zusammenfassend zeigen alle drei Beobachtungselemente warme Permafrostverhältnisse für die Berichtsperiode im Vergleich mit den vorhergehenden fünf Jahren seit dem Rekordsommer 2009. Dies resultiert insbesondere von dem äusserst warmen Jahr 2009 mit einem sehr warmen Herbst und frühem Einschneien im Oktober.

Resumé

Ce rapport sur le permafrost en Suisse couvre les deux années hydrologiques 2008/2009 et 2009/2010. Il s'agit du second rapport de la phase d'implémentation 2007–2010 du Réseau Suisse de Monitoring du Pergélisol PERMOS et le cinquième depuis 2000. Il conclut les 10 premières années officielles de l'opération PERMOS, qui débuta par une première phase pilote en 2000. Trois éléments d'observation complémentaires sont mesurés dans le cadre de PERMOS : températures du sous-sol, changements dans la teneur en glace et vélocités de fluage du pergélisol. Le monitoring est conduit sur quatre catégories de formes : les parois rocheuses, les crêtes, les éboulis et les glaciers rocheux. A partir de ces mesures, PERMOS vise à fournir une image aussi précise que possible de l'état et de l'évolution du permafrost dans les Alpes suisses.

Les conditions météorologiques en 2008/2009 ont été caractérisées par hiver précoce et long, suivi par un printemps chaud, un été changeant et un automne 2009 extrêmement chaud. Conséquence de ces conditions, la couverture neigeuse a rapidement disparu à la mi-juin, malgré de nouvelles chutes de neige enregistrées par plusieurs stations. 2009 a été 1.2 °C plus chaud que la normale. L'hiver 2009/2010 a été relativement froid et le printemps, l'été et l'automne suivants ont été caractérisés par un temps variable et des températures normales. Malgré un manteau neigeux généralement inférieur à la normale, la fonte s'est produite seulement vers la fin juin. 2010 fut 0.2 °C plus chaud que la normale. Seul 1996 a connu des températures plus froides au cours des 22 dernières années.

Les températures de la proche surface enregistrées durant cette période reflètent les conditions atmosphériques. En particulier, les fortes chaleurs de la fin de l'été 2009 ont engendré des températures de surface élevées. Durant l'été 2010 les conditions ont été à nouveau plus froides, mais les températures de surface furent en général plus élevées que durant la période correspondant au précédent rapport. En conséquence, les profondeurs des niveaux actifs ont été plus importantes que durant la période précédente, alors qu'elles étaient restées généralement stables durant les cinq années précédentes. Les températures du sous-sol à environ 10 m de profondeur ont également été au-dessus de la moyenne des années précédentes. En particulier, les températures minimales dans les sites riches en neige ont atteint des valeurs record pour les deux années. Les résistivités électriques de la période 2008–2010 n'ont pas montré de signal clair d'évolution, mise à part au Schilthorn, où des valeurs exceptionnellement basses ont été observées. Cela est attribué à l'effet cumulatif de ces deux années chaudes, que l'on peut aussi observer dans les températures mesurées en forage et dans les profondeurs de la couche active. Après les vitesses très élevées qu'ont connues les glaciers rocheux en 2003 et 2004, les vitesses diminuèrent jusqu'en 2006. Depuis 2007, la plupart des sites montrent une légère accélération. Alors que les changements relatifs des vitesses horizontales de surface montrent d'importantes variations entre 2001 et 2005, les changements furent beaucoup plus faibles durant les années suivantes. Finalement, durant les deux années couvertes par ce rapport, neuf éboulements d'un volume supérieur à 1000 m^3 et situés à des altitudes comprises entre 2700 m et plus de 4000 m ont été documentés dans les secteurs à permafrost des Alpes suisses.

En résumé, les trois éléments d'observation attestent de conditions très chaudes pour le permafrost au cours de cette période, en comparaison avec les 5 années qui suivirent les records de l'été 2003. Cela résulte en particulier de l'année 2009 très chaude, avec une fin d'été et un automne chaud, ainsi que des chutes de neige précoces en octobre.

Riassunto

Questo rapporto sul permafrost nelle Alpi svizzere copre i due anni idrologici 2008/2009 e 2009/2010. Si tratta del secondo rapporto della fase di implementazione 2007–2010 e del quinto rapporto in assoluto della Rete Svizzera di Monitoraggio del Permafrost PERMOS. Esso completa i primi 10 anni di funzionamento ufficiale di PERMOS, la cui fase pilota è iniziata nel 2000. La strategia di osservazione di PERMOS segue oggi un approccio basato sulle forme geomorfologiche e suddiviso nell'analisi di tre fenomeni complementari tra loro. Questi tre fenomeni sono la temperatura del suolo, i cambiamenti di tenore in ghiaccio e le velocità di reptazione del permafrost riferiti a quattro forme geomorfologiche principali: pareti rocciose, creste, falde di detrito e ghiacciai rocciosi. Sulla base delle misure eseguite, PERMOS ha lo scopo di definire un quadro globale dello stato e dell'evoluzione del permafrost nelle Alpi svizzere.

Le condizioni meteorologiche durante l'anno idrologico 2008/2009 sono state caratterizzate da condizioni invernali precoci e persistenti, seguite da una primavera calda, un'estate variabile e l'autunno eccezionalmente caldo del 2009. Di conseguenza, la copertura nevosa si è sciolta precocemente a metà giugno nonostante le nuove nevicate che hanno caratterizzato numerose località. Il 2009 è stato 1.2 °C più caldo rispetto alla media a lungo termine. L'inverno 2009/2010 è stato relativamente freddo e la primavera, estate e autunno 2010 seguenti sono stati caratterizzati in generale da condizioni meteorologiche variabili e da temperature nella norma. Nonostante quantità di neve generalmente sotto la media, la fusione nivale è iniziata solo verso la fine di giugno. Il 2010 è stato 0.2 °C più caldo rispetto alla media a lungo termine, anche se negli ultimi 22 anni solo nel 1996 la temperatura media è stata più bassa.

Le temperature in prossimità della superficie del suolo misurate durante il periodo coperto dal presente rapporto riflettono le condizioni atmosferiche. In special modo durante la fine estate molto calda del 2009, si sono raggiunte delle temperature della superficie del suolo nella stessa gamma di valori estremi registrati nel 2003. Durante l'estate 2010 le condizioni sono state al contrario più fredde, anche se in generale le temperature di superficie erano più elevate rispetto al periodo coperto dai precedenti rapporti. Di conseguenza, lo spessore dello strato attivo è risultato significativamente importante per entrambi gli anni 2008/2009 e 2009/2010 quale risultato delle condizioni estive calde, in particolar modo durante il 2009. Lo spessore dello strato attivo è comunque rimasto più o meno stabile attorno ai valori registrati nei 5 anni precedenti. Le temperature del suolo a circa 10 m di profondità erano anch'esse sopra la media degli anni precedenti. In particolare, le temperature minime del suolo nei siti con maggiore innevamento sono state le più elevate per entrambi gli anni trattati in questo rapporto. Le resistività elettriche misurate nel periodo 2008–2010 presentavano un chiaro segnale di cambiamento in un solo sito: dei valori eccezionalmente bassi sono stati osservati allo Schilthorn. Questo fatto è stato attribuito all'effetto cumulato dei due anni idrologici relativamente caldi, ciò che è pure visibile nella temperatura dei sondaggi e nello spessore dello strato attivo. Dopo velocità di flusso dei ghiacciai rocciosi eccezionalmente elevate del 2003 e del 2004, queste sono diminuite in maniera importante fino al 2006, anche se dal 2007 la maggior parte dei siti monitorati presenta una lieve accelerazione. Benché i cambiamenti relativi nelle velocità orizzontali presentassero delle importanti variazioni tra il 2001 e il 2005, questi cambiamenti sono stati molto più limitati negli anni più recenti. Infine, durante il periodo coperto da questo rapporto nove eventi di crollo con un volume di almeno 1000 m^3 ad altitudini comprese tra 2700 e >4000 m slm sono stati documentati nelle aree caratterizzate dal permafrost delle Alpi svizzere.

Ricapitolando, i tre fenomeni osservati indicano delle condizioni del permafrost molto calde per il periodo 2008/2009 e 2009/2010 rispetto ai cinque anni precedenti, che hanno seguito l'estate eccezionalmente calda del 2003. Ciò risulta soprattutto dall'anno 2009 molto caldo, caratterizzato da un autunno caldo seguito da nevicate precoci durante il mese di ottobre.

Resumaziun

Quest rapport pertucont la schelira permanenta en las Alps svizras cuviera ils dus onns hidrologics 2008/2009 e 2009/2010. Igl ei il secund rapport dalla fasa da implementaziun 2007–2010 dalla reit svizra per survigilonza della schelira permanenta (PERMOS). Medemamein eis ei il 5avel rapport ella seria da rapports, il qual cumpletescha ils emprems 10 onns ufficials da PERMOS dapi l'incepziun cun ina fasa da pilot egl onn 2000. Ozildi suonda la strategia d'observaziun da PEROMS ina disposiziun basada sin la fuorma dil terren cun treis elements d'observaziun, ils quals cumpleteschan in l'auter. Ils elements d'observaziuns consistan ord la temperatura dil terren, midadas dil cuntegn dil glatsch e la spertadad dil ruschnar dalla schelira permanenta. Las quater fuormas da terren consideradas ein preits crap, crestas, gondas e glatschers cumpacts. Basond sin questas observaziuns emprova PERMOS da furnir in cumplet maletg dil stadi e la midada dalla schelira permanenta en las alps Svizras.

Las condiziuns meteorologicas dils onns 2008/2009 ein caracterisadas dad in baul e liung unviern, suandaus dad ina primavera caulda, ina stad cun aura varionta ed in extrem cauld atun 2009. Sco resultat da quellas condiziuns ei la cozza da neiv luada entochen miez zercladur, quei malgrad che entginas staziuns d'observaziuns havevan mesirau cozzas da neiv da record. Igl onn 2009 ei staus 1.2 °C pli caulds che la media da liunga durada. Il suandont unviern 2009/2010 ei staus relativamein caulds e duront la primavera, la stad ed igl atun ei l'aura stada variabla cun temperaturas normalas. Era sche la cozza da neiv ei stada sut la media eis ella bu luada avon la fin da zercladur. La temperatura media digl onn 2010 ei stada 0.2 °C pli caulda che la temperatura media da liunga durada. Duront ils davos 22 onns ei la temperatura denton stada pli bassa mo igl onn 1996.

Las temperaturas datier dalla surfatscha mesiradas duront la perioda da rapport reflectan las condiziuns atmosfericas. Specialmein la caulda finiziun dalla stad 2009 ha caschunau aultas temperaturas da surfatscha dil terren, las qualas eran el medem interval sco duront igl onn 2003. Duront la stad moderada 2010 ein las condiziuns puspei stadas pli freidas, mo en general ein las temperatura dalla surfatscha stadas pli aultas che duront la perioda d'observaziuns precendenta. Sco resultad dallas condiziuns cauldas ein las cozzas activas stadas significantamein pli profundas per omisdus onns da rapport, quei specialmein duront igl onn 2009. Ils tschun onns avon eran ellas stadas pli u meins stablas. Las temperaturas dil terren en ina profunditad da 10 meters ein era stadas sur la media dils onns precedents. Particularmein ein las temperaturas da terren minimalas en loghens cun bia neiv stadas a livels da record per omisdus onns da rapport. Las observaziuns dalla resistivitad duront la perioda da 2008 tochen 2010 han mussau evidenza per evoluziun mo en in liug da observaziun, numnadamein al Schilthorn, nua che valetas extraordinari bassas ein vegnidas observadas. Quella evoluziun ei il resultat d'in effect cumulativ dils dus onns caulds duront la perioda da rapport. Il medem effect ei era veseivels ella temperatura dalla fora da sondagi al Schilthorn ed ell profunditad dallas cozzas activas. Suenter las spertadads extraordinarias da moviment dils glatschers cumpacts duront ils onns 2003 e 2004 ein quellas idas anavos entochen igl

onn 2006. Naven digl onn 2007 han ils biars loghens d'observaziun mussau mo ina pintga augmentaziun da spertadad. Era sche las midadas relativas da spertadad horizontala han ina gronda variaziun duront la perioda da 2001 entochen 2004 ein ellas stada bia pli pintgas duront ils onns recents. Duront la perioda da rapport ein nov eveniments da curdada da crappa cun in volumen da silmeins 1000 meters cubic ed ina altezia denter 2700 e 4000 meters sur mar vegni documentai en regiuns da schelira permanenta en las alsp Svizras.

Sco conclusiun san ins dir che tuts treis elements d'observaziun indicheschan condiziuns fetg cauldas da schelira permanenta duront las perioda da rapport cumparegliau cun ils 5 onns precedents, ils quals han suandau la stad da record digl onn 2003. Quellas indicaziuns ein il resultad d'in fetg cauld onn 2009 cun in cauld atun e neiv l'entschatta october.

Contents

1 Introduction

This report on permafrost in the Swiss Alps covers the two hydrological years 2008/2009 and 2009/2010. It is the second report of the four-year implementation phase 2007–2010 of the Swiss Permafrost Monitoring Network PERMOS and the 5th of its kind. It complements the first 10 years of official PERMOS operation, which started with a first pilot phase in the year 2000.

During this past decade, PERMOS developed from a loose network of research sites from several institutions towards an operational monitoring network with a coordinating office, partner institutions, and a Steering and Scientific Committee. PERMOS can build on substantial and secured financial support by the joint partnership of the Swiss GCOS Office at MeteoSwiss, the Swiss Federal Office for the Environment (FOEN), and the Swiss Academy for Sciences (SCNAT). PERMOS is implemented in the responsible federal monitoring structures of GCOS Switzerland and is part of the Swiss cryosphere monitoring. Within the international framework, PERMOS is one of the early components of the Global Terrestrial Network for Permafrost (GTN-P) of the worldwide climate-monitoring program GCOS/GTOS of the World Meteorological Organization (WMO) and others (UNESCO, UNEP, ICSU, FAO). Within the five-tiered principle proposed for the Global Hierarchical Observing Strategy (GHOST, cf. Harris et al. 2001 for adaptation to permafrost observation) the national network mainly contributes to Tiers 3 and 4. It provides observations to sample the range of environmental variation in permafrost thermal state as in Tier 3 (regional observations at intermediate depths and regular time intervals) and aims to describe representative permafrost conditions based on the observation sites and elements as in Tier 4 (ground thermal conditions to provide representative permafrost conditions).

The connection between climate and subsurface thermal regime is not straightforward since snow conditions, surface and subsurface characteristics, subsurface ice, and mountain topography can alter or mask changes in atmospheric conditions (Chapter 2) when they propagate into the subsurface. The PERMOS observation strategy has continuously evolved and the observed elements have repeatedly been evaluated and updated based on gained experience as well as findings from research. Today, the PERMOS observation strategy follows a landform-based approach because differences due to varying climate conditions in Switzerland are considered to be smaller than the differences in the subsurface thermal regime caused by topography and surface and subsurface conditions of the different landforms. The main landforms distinguished are rock walls (e.g., Eiger North Face), crests (e.g., Matterhorn-Hörnligrat, Schilthorn, Stockhorn), talus slopes (e.g., Les Attelas, Lapires, Muot da Barba Peider), and rock glaciers (e.g., Murtèl-Corvatsch, Réchy, Schafberg). PERMOS today builds on three observation elements in order to capture these features: (1) ground temperatures, (2) changes in ice content, and (3) permafrost creep velocities. The three elements complement each other in order to deliver a comprehensive picture of permafrost state and changes in the Swiss Alps.

(1) The core of the network are **ground temperatures** measured in boreholes, which provide direct evidence of permafrost (Chapter 3). Borehole temperatures are complemented by temperature measurements at or near the surface at locations around the site in order to capture the influence of differing surface cover types and topographic settings, which cause a high spatial variability of ground surface temperatures (GST). The temperature changes at depth integrate and filter the signal from the surface and reflect trends delayed, but more clearly. They are however often influenced by effects of 3D geometry and latent heat. For temperatures little below the

Table 1.1: Overview of the PERMOS sites, their morphology and the types of measurement carried out. Sites are sorted regionally and PERMOS Reference Sites are marked in bold. T stands for temperature site, K for kinematics site, K(AP) for sites where only air photos are taken. BH=borehole, GST=ground surface temperature, RST=rock surface temperature, ERT=electrical resistivity tomography, AS=aerial survey, TGS=terrestrial geodetic survey.

Site	Type	Region	Main Morphology	BH	GST	RST	ERT	AS	TGS
Grosses Gufer	K	Bernese Oberland	Rock glacier					x	x
Schilthorn	T	Bernese Oberland	Crest	x	x	x	x		
Dreveneuse	T	Chablais	Talus slope	x	x		x		
Corvatsch	T K	Engadine	Rock glacier	x	x	x	x	x	x
Flüela	T	Engadine	Talus slope	x	x		x		
Muot da Barba Peider	T	Engadine	Talus slope	x	x			x	
Muragl	T	Engadine	Rock glacier	x				x	x
Schafberg	T	Engadine	Talus slope	x	x			x	
Aget	K	Lower Valais	Rock glacier		x				x
Alpage de Mille	K	Lower Valais	Rock glacier		x				x
Gentianes	T	Lower Valais	Moraine	x			x		
Lapires	T K	Lower Valais	Talus slope	x	x	x	x		x
Les Attelas	T	Lower Valais	Talus slope	x	x		x		
Réchy	K	Lower Valais	Rock glacier		x	x		x	x
Tsarmine	K	Lower Valais	Rock glacier		x				x
Tsaté	T	Lower Valais	Crest	x	x				
Yettes Condjà	K	Lower Valais	Rock glacier		x				x
Monte Prosa	K	Ticino	Rock glacier		x				x
Stabbio di Largario	K	Ticino	Rock glacier		x				x
Valle di Sceru	K	Ticino	Rock glacier		x				x
Gemmi-Furggentälti	K	Upper Valais	Rock glacier		x			x	x
Gruben	K(AP)	Upper Valais	Rock glacier					x	
Matterhorn	T	Upper Valais	Crest	x					
Ritigraben	T	Upper Valais	Rock glacier	x	x				
Stockhorn	T	Upper Valais	Crest	x	x		x		
Turtmanntal-Hungerlitälli	K	Upper Valais	Rock glacier		x			x	x
Gemsstock	T	Urner Alps	Crest	x			x		

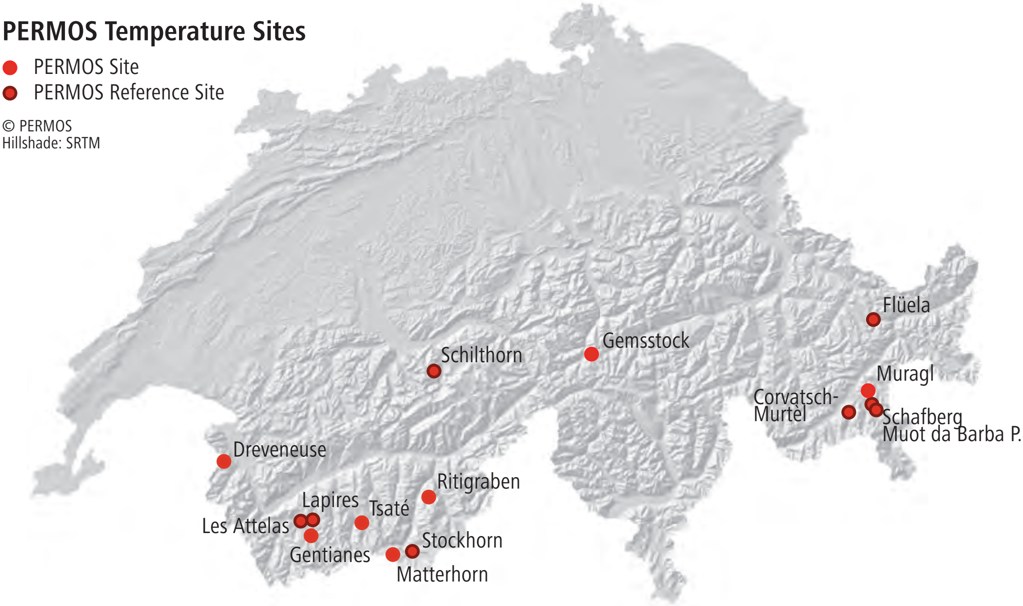


Figure 1.1: PERMOS temperature sites.

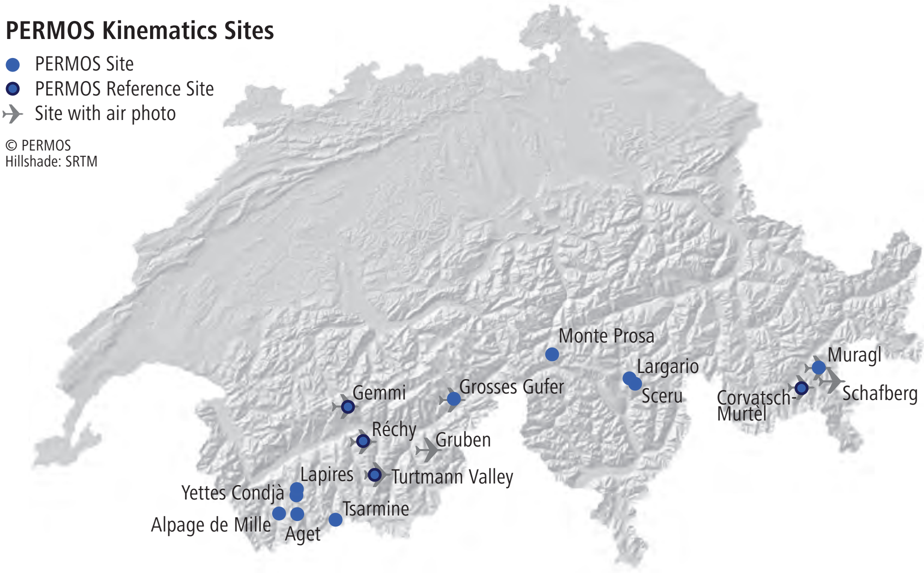


Figure 1.2: PERMOS kinematics sites.

melting point, the latter takes up an additional energy input into the subsurface and only small or no changes can be observed in ground temperatures.

(2) An electrical resistivity tomography (ERT) monitoring is installed at a number of sites since 2004. Based on the differing electrical resistivities of frozen and unfrozen ground and the calculation of their changes between different surveys the **changes in subsurface ice and unfrozen water content** can be observed. ERT monitoring is integrated into the regular reporting since the 3rd PERMOS Report (PERMOS 2009) and results are described in Chapter 4.

(3) Air photos have been taken since the start of PERMOS, which allow the observation of **creep velocities in ice-rich permafrost features** by photogrammetric analyses. It has recently been shown that with increasing ground temperature, the creep velocities of rock glaciers also increase. In a 2-year pilot phase 2008–2010 in-situ measurements from terrestrial surveys were included in PERMOS (4th PERMOS Report, PERMOS 2010) and are an approved part of the network since 2010. A short overview of the monitoring strategy is given in this report (Chapter 5). Fast mass movements from permafrost areas (i.e., larger rock fall events) are documented since the last report in addition to the creep velocities.

In 2010, the PERMOS network includes 15 temperature sites where borehole temperatures, GST and ERT are measured, and 14 kinematics sites, where terrestrial surveys are performed and air photos are regularly taken (Tab. 1.1, Figs. 1.1 and 1.2). The sites have been evaluated by the PERMOS Scientific Committee (SciCom) in 2007 and in 2009 based on their relevance, feasibility and scientific and societal interest. Sites where long-term monitoring is most reasonable and feasible have been designated as PERMOS Reference Sites. They build the corner stones of the network and are treated with priority.

The field work and site maintenance of the PERMOS network are carried out by the PERMOS partner institutes, which also carry the main work load of data acquisition and processing:

- ETH Zurich: Institute for Geotechnical Engineering (IGT–ETH)
- University of Berne: Department of Geography (UniBE)
- University of Fribourg: Department of Geosciences, Alpine Cryosphere and Geomorphology (UniFR)
- University of Lausanne: Faculty of Geosciences and Environment, Geography Institute (UniL)
- University of Zurich: Department of Geography, Glaciology, Geomorphodynamics & Geochronology (UZH)
- WSL Institute for Snow and Avalanche Research Davos (SLF)

The last chapter of the PERMOS report traditionally presents selected aspects of permafrost monitoring. In this issue, the topic are the exceptionally high creep velocities that have recently been observed at a number of rock glaciers. Features with such high velocities are difficult to include in long-term monitoring programs like PERMOS, but research about their driving processes is essential for the understanding of permafrost creep phenomena and their interaction with climate and topography. A new research project has been initiated by the IGT–ETH at the foot of the Furggwanghorn in the Turtmann Valley, close to the PERMOS Kinematics Site Turtmanntal-Hungerlitälli, to investigate the potential relation of the fast creep velocities and the thermal conditions of the rock glacier. An exceptionally fast creeping rock glacier that is topographically driven can be observed at Grabengufer in the Matter Valley, just above the village of Randa. This site is regularly studied by the UniFR.

2 Weather and Climate

In this section, we describe the weather and climate conditions that have the most important influence on the inter-annual variations of the ground thermal regime: air temperature and timing and thickness of the snow cover. The general weather and climate information is taken from the reports by MeteoSwiss (MeteoSwiss 2008, 2009, 2010), the snow information is provided by SLF.

Air temperature is the driving factor for changes in GST in times and areas without any thicker snow cover. If a snow cover is present, it thermally insulates the ground from the conditions in the atmosphere. Therefore the time of the first snow fall, the duration and thickness of the snow cover, and the time when the ground surface becomes snow free in spring are relevant. These parameters can be determined based on the continuous recording of GST (cf. Chapter 3): the percolation of melt water provokes a sudden increase to 0 °C at the time when the entire snow cover is wet down to its base (start of the zero curtain). Then, the GST remains almost stable until the snow cover completely disappears (date when the terrain becomes snow free).

2.1 Air Temperatures and Snow Cover in 2008/2009

The meteorological conditions during the period 2008/2009 were characterised by an early and long winter from October 2008 to March 2009, an above average warm spring (4th warmest April and 2nd warmest May since the beginning of the measurements 1864), a changeable summer with a hot period in August, and a dry autumn. The year 2009 was the 7th warmest year since 1864 with 1.2 °C above the mean of the period 1961–1990. Six of the seven warmest years were recorded in the past decade (since 2000).

The winter 2008/2009 started at the end of October with repeated and exceptionally abundant snowfall events both North and South of the Alps. November and December were also characterised by particularly intense solid precipitation, mainly induced by southerly weather situations in December. After a pause in January 2009, with below-average precipitation for the time of year, intense snowfall resumed in February leading to snow depth records at several stations. March was also very snow-rich and the first half of April was warm and sunny, before further snowfalls occurred and made for an exceptionally snow-rich spring (Figs. 2.1–2.3).

The warm and dry spring 2009 favoured an intense and rapid melting of the snow cover. In the northern regions like the Bernese Oberland, where the winter snow accumulation was smaller, the snow cover disappeared completely by mid-June. This is about 2 weeks earlier than usual in the preceding decade. At some locations it was even at the earliest date since the beginning of the PERMOS GST measurements in the second half of the 1990s (Fig. 2.3a). The snow free date occurred later and close to the mean value in the inner Alpine regions like the Lower Valais because of a thicker winter snow cover (Fig. 2.3b). The snow cover persisted much longer in the southern Alps.

The two months May and August 2009 were hot, with air temperatures ca. 3–4 °C above the climatic mean 1961–1990. The period between, June and July, was changeable and ca. 1–1.5 °C warmer than average. September was again sunny and warm. Mean summer temperatures 2009 (JJA) were ca. 2 °C above average all over Switzerland (Figs. 2.4 and 2.5).

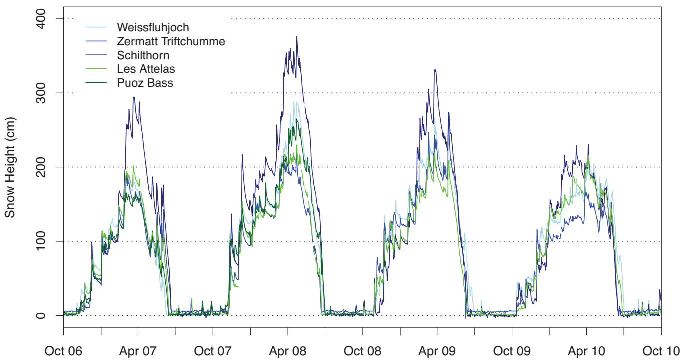


Figure 2.1:
Evolution of the snow depth at five measurement stations in the Swiss Alps during a four year period including the winters 2008/2009 and 2009/2010. Data provided by SLF.

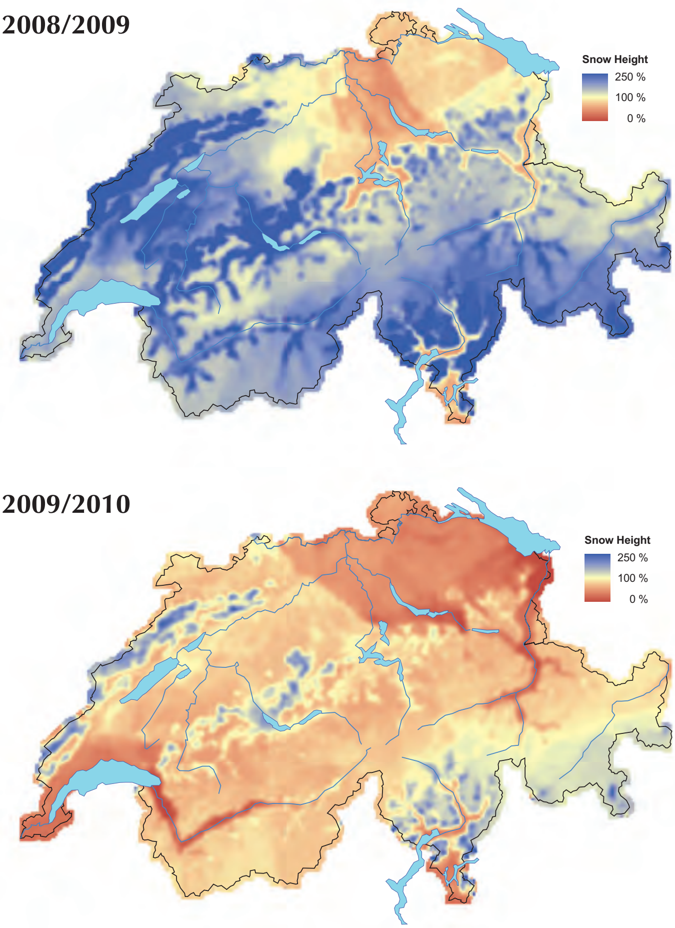


Figure 2.2:
Regional variability of deviations of winter snow amounts for the years 2009 (top) and 2010 (bottom), deviation from the mean value 1971–2000 in percent. Figure provided by C. Marty, SLF.

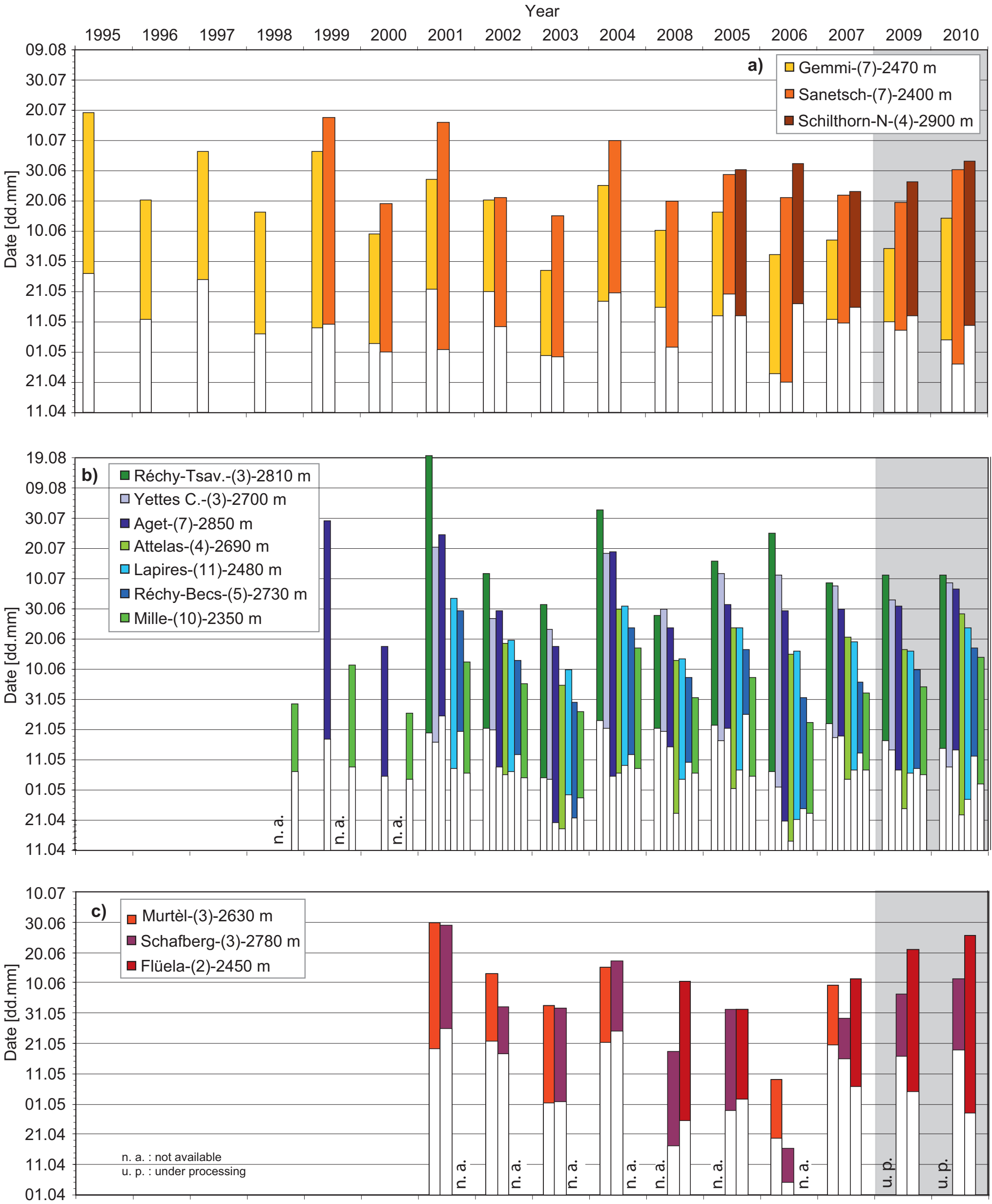
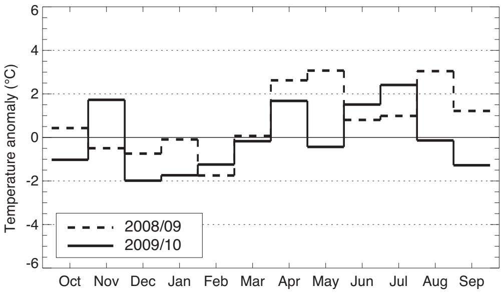


Figure 2.3: Dates of snow melt (1995–2010) deduced from GST time series: a) Bernese Oberland, b) Lower Valais, and c) Engadine. The bottom and top of the coloured bars indicate the start and the end of the zero curtain period. If several GST-series are measured on a site, the mean is calculated. Legend: site–(number of measurements)–mean elevation.



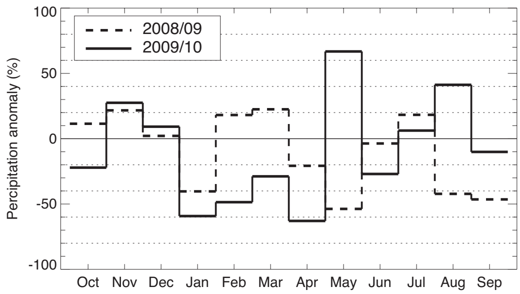
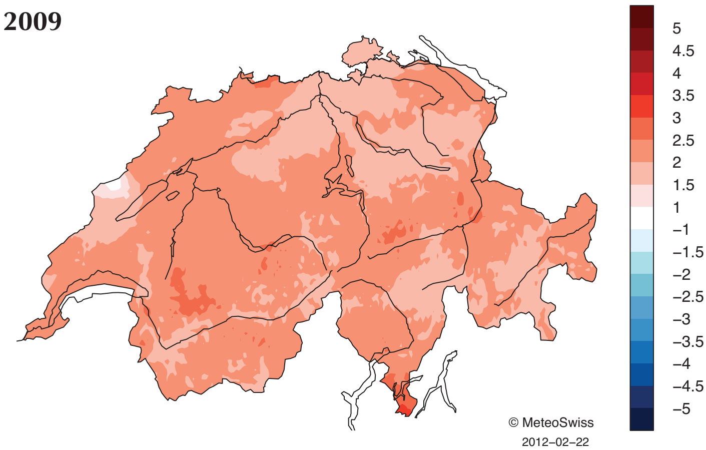


Figure 2.4: *Mean monthly anomalies of air temperatures (left) and precipitation (right) from the long-term climatic mean (period 1961–1990) for the climate station at Weissfluhjoch and the reporting period. Graph compiled by M. Huss, UniFR, data provided by MeteoSwiss.*



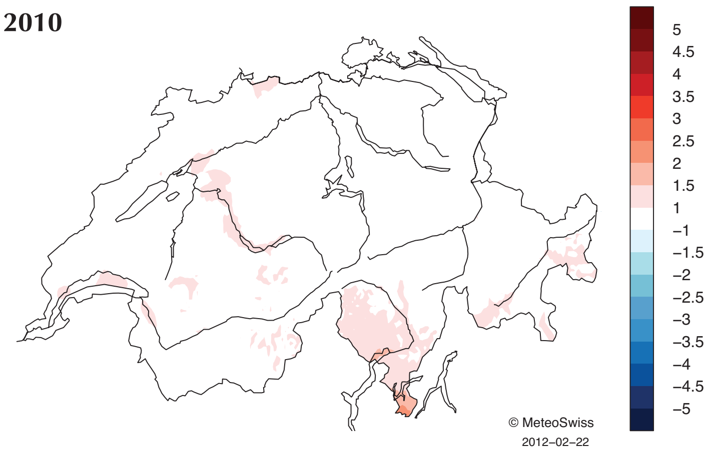


Figure 2.5: *Regional variability of mean summer air temperatures (May–September) for the year 2009 (top) and 2010 (bottom), deviation from the mean value 1961–1990 in degrees Celsius. Figure provided by MeteoSwiss.*

2.2 Air Temperatures and Snow Cover in 2009/2010

The hydrological year 2009/2010 started with a very warm autumn and a cold period from December 2009 to February 2010 with air temperatures about 1.5–2 °C lower than the mean 1961–1990 in the mountain areas. Spring, summer, and autumn 2010 were all characterised by variable weather conditions, interrupted by a heat wave in July, and can be described as normal. Overall, the year 2010 was 0.2 °C warmer than the long-term average. In the past 22 years, however, only in 1996 temperatures were lower.

In addition to the low air temperatures, below-average snow depths in many areas characterise the winter 2009/2010. Only the Upper Engadine and Southern Grisons registered snow depths that were slightly above average. After a snow-rich start in October 2009 in the Central and Eastern Alps, there was very little precipitation in November and temperatures fluctuated strongly. A southerly situation caused intense snowfall at the end of the month in the southern and central regions. In December, snowfall occurred repeatedly with changing weather causing snow depths that were marginally above average. In contrast, January 2010 was very dry until an intense snowfall occurred at the end of the month. February was cold and dry with repeated yet weak precipitation events and this continued until mid-March, when a particularly snow-rich event occurred in the South. The beginning of April was also snowy and cold before spring set in at the end of the month (Figs. 2.1–2.3).

The snow melt in 2010 started early at many sites and was caused by a warm, dry and sunny end of April. However, the melting of the snow cover was slowed down by a colder and cloudy May. These conditions resulted in a snow free date close to or even later than the mean value of the PERMOS observations for most sites.

Summer 2010 can be divided into three phases: a wet period until end of May, a hot summer period of about one month until end of July, and another wet period with influence of polar air until the end of August. Overall, summer 2010 was little more than 1 °C warmer than average. Air temperatures in autumn 2010 were in the range of the long-term mean, at higher elevations even below (Figs. 2.4 and 2.5).

3 Ground Temperatures

The basis of the permafrost monitoring is the observation of the subsurface thermal conditions and their changes. Ground temperatures are measured in and around boreholes at 15 sites in bedrock and in loose debris on rock glaciers, scree slopes, or moraines (see Tab. 1.1, Fig. 1.1).

GST are measured to characterise the influence of snow and surface cover as well as of topography (slope, aspect, and elevation) on the thermal regime of the ground. The variations of GST mainly reflect short-term variations in atmospheric and snow conditions and their changes are the main driving factor of changes in permafrost conditions. Measurements in the vicinity of the drill sites further help to assess the spatial variability at the site and the representativeness of the boreholes. Measurement devices are installed at three main types of locations: (i) in steep bedrock, where the influence of topography on ground temperatures is maximal and a snow or debris cover is absent; (ii) in gently sloping or flat bedrock, where the effect of snow cover becomes important, and (iii) within coarse blocks or debris mantled slopes, where effects of air circulation can be observed. In addition, the bottom temperature of the snow cover (BTS, Haeberli 1975) is measured at two sites every year for comparison and to observe spatial patterns.

The active layer thickness (ALT) is a reflection of the local snow and atmospheric conditions reigning during the current and previous year, as well as of the local ground characteristics. It is defined by the maximum depth of the 0 °C isotherm in the ground during one year, and can be approximated using linear interpolation from thermistors in boreholes. Ground temperatures measured at medium depth in boreholes allow the observation of seasonal and interannual temperature variations. The temperatures at ca. 10 m depth do not react to short-term fluctuations but still show the seasonal variations and therefore particularly reveal the importance of both air temperatures and snow depth as regulators of ground temperatures at the regional to national scale. Here, minimum temperatures are typically measured in summer because it takes about six months for a signal at the surface to penetrate. The seasonal signal is hardly visible at ca. 20 m depth (expect for reasons of steep geometry such as for example in the borehole on the Matterhorn Hörnligrat) and the time lag for signals from the surface is in the order of years. Here, temperature changes are governed by long-term changes at the surface.

3.1 Near-surface Temperatures

3.1.1 Bedrock

Measurement activities of near-surface rock temperatures at the 35 sites of the network yielded only nine complete temperature time series of hourly resolution during the hydrological year 2008/2009 and 21 during 2009/2010 (Table 3.1). Some data have been recovered for many of the remaining sites, but were not complete enough to justify the calculation of annual averages. A synopsis of mean annual rock temperatures (MART) is provided in Figure 3.1. The left part of the illustration shows that MART are generally higher than mean annual air temperatures (MAAT). In south-exposed near-vertical locations this difference amounts to up to 10 °C, in north-exposed locations MART is only slightly higher than MAAT. Due to the much larger spread in exposition to solar radiation, the range of relative rock temperatures in steep terrain is about 10 °C whereas it is about 5 °C underneath a seasonal snow cover. The right part of Figure 3.1 shows that inter-annual fluctuations of tempera-

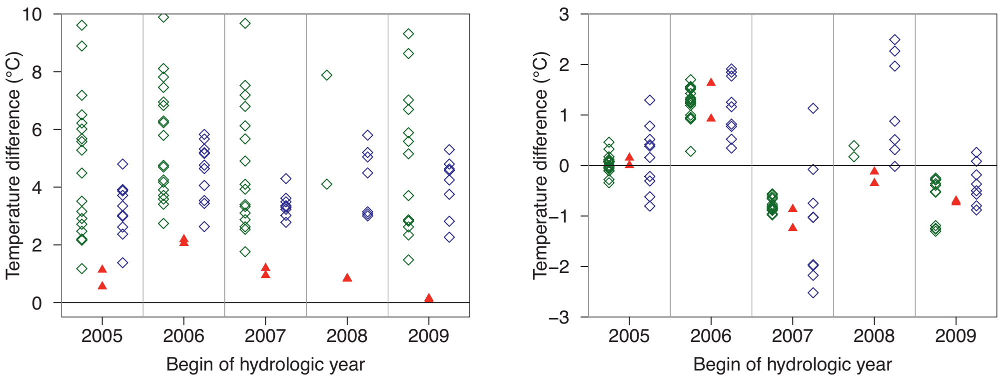


Figure 3.1: *Mean annual rock temperatures plotted for the past 5 years including the reporting period: relative to the mean air temperature 1961–1990 (left) and relative to the previous year (right). Green: steep bedrock without the influence of snow, blue: gently inclined rock with seasonal snow cover, red: air temperature at Jungfraujoch and Corvatsch (Data: MeteoSwiss). Mean air temperature was calculated for the elevation of each measurement site based on data from Jungfraujoch and Corvatsch and a constant lapse rate.*

tures in steep rock correlate closely with air temperature changes whereas rock subject to a seasonal snow cover exhibits much larger variability. For steep as well as flat rock surfaces, 2008/2009 was slightly warmer than the previous year. The year 2009/2010 was about 1 °C colder than 2008/2009.

Incomplete data series resulted mostly from broken data loggers or service visits during which not all loggers could be accessed. A problem with the infrared-port in the old version of the data loggers used caused a high rate of data loss during the reporting period. This has been overcome with a new generation of data loggers that are read out wirelessly.

3.1.2 Loose Debris

The GST measurements in loose debris material were continued at 17 PERMOS Sites, which are instrumented with 3–21 single-channel temperature data loggers (Tab. 3.2). The loggers are typically located on rock glaciers, talus slopes, or moraines with slope angles between 0 and ca. 40°. At these sites a relatively thick snow pack develops during winter (snow depth from 0.5 to >3 m), except for a few wind-exposed sites. The parameters obtained by the GST measurements are:

(i) the duration of the snow cover (as described in Chapter 2),
(ii) the Ground Freezing Index (GFI), which is the sum of all daily negative ground temperatures measured during winter and indicates how cold a winter is at the ground surface (a lower GFI results from a colder winter), and
(iii) the Mean Annual Ground Surface Temperature (MAGST), which results from the combination of (i), (ii) and summer temperatures.

Major efforts have been undertaken for this report to integrate and homogenise the GST time series. Figures 3.2 and 3.3 now include data from more sites than in the previous reports. Further, in the Annex a detailed over-

Table 3.1: RST sites and mean annual rock temperatures (MART) for the reporting period. MART is only calculated if ≥360 days of measurement are available.

Name	Region	Elev. (m a.s.l.)	Slope (°)	Aspect	MART 08/09	MART 09/10
Birg East 2	Bernese Oberland	2620	0	0	1.45	1.27
Birg vertical	Bernese Oberland	2670	85	205	6.01	4.82
Birg West 2	Bernese Oberland	2680	22	130	n.a.	n.a.
Eigerfenster	Bernese Oberland	2860	90	325	n.a.	–0.77
Eismeer	Bernese Oberland	3150	87	100	n.a.	n.a.
Engital	Bernese Oberland	2410	10	130	2.96	2.08
Jungfrau East Ridge N	Bernese Oberland	3750	55	344	n.a.	–7.41
Jungfrau East Ridge S	Bernese Oberland	3750	70	145	n.a.	0.42
Moench West Ridge	Bernese Oberland	3550	72	288	n.a.	n.a.
Schilthornhuette	Bernese Oberland	2450	0	0	n.a.	n.a.
Schwarzgrat	Bernese Oberland	2800	0	0	0.35	n.a.
BB-h01	Lower Valais	2600	0	0	n.a.	n.a.
BB-v01	Lower Valais	3100	90	75	n.a.	n.a.
BB-v02	Lower Valais	3120	75	308	n.a.	n.a.
BB-v03	Lower Valais	3140	95	198	n.a.	n.a.
BB-v04	Lower Valais	2590	85	278	n.a.	n.a.
BB-v05	Lower Valais	2590	90	50	n.a.	n.a.
La-h01	Lower Valais	2735	0	0	n.a.	n.a.
La-v01	Lower Valais	2380	95	325	n.a.	2.83
La-v02	Lower Valais	2730	95	39	n.a.	2.89
La-v03	Lower Valais	2720	90	140	n.a.	n.a.
La-v04	Lower Valais	2700	80	225	n.a.	3.82
La-v05	Lower Valais	2770	100	341	n.a.	0.34
Corvatsch Hubbel	Engadine	2545	0	0	n.a.	3.74
Corvatsch Mid. Flat	Engadine	2690	8	320	3.20	2.63
Corvatsch Mid. Ridge	Engadine	2784	85	278	1.49	1.09
Corvatsch Snow Canon	Engadine	2649	0	0	3.31	2.51
Corvatsch Top Flat	Engadine	3300	0	0	n.a.	–2.22
Corvatsch Top Gate	Engadine	3285	72	333	n.a.	–3.25
Corvatsch Top Ridge	Engadine	3300	58	181	n.a.	1.05
Fuorcla	Engadine	2740	11	344	2.16	2.25
Fuorcla North	Engadine	2765	23	11	3.31	2.81
Mandra East	Engadine	2805	90	88	n.a.	2.83
Mandra South	Engadine	2830	98	185	n.a.	5.72
Murtel Front	Engadine	2630	15	20	n.a.	n.a.

view of the most important sites with measurement locations and trends of the past decades is now included (pp. 70–79).

Ground Freezing Index

The values of the GFI for winter 2008/2009 were relatively high (Fig. 3.2). In some places they were also higher than in previous warm winters (such as 2000/2001 or 2002/2003), which is probably due to an early thick snow pack in autumn 2008. Regional and site specific conditions, however, modify the intensity of the ground cooling and the results are somewhat heterogeneous. The general pattern shows a more pronounced cooling effect in the inner parts of the Alps (e.g., Lower Valais) than in the northern parts (e.g., Bernese Oberland).

The values of the GFI for winter 2009/2010 were close to the mean of the past decade or higher. The heterogeneity was even higher than in the preceding winter.

Mean Annual Ground Surface Temperature

MAGST values are illustrated using a running average of monthly means in Figure 3.3. The running MAGST remained quite stable in the northern part of the Alps from October 2008 to mid-summer 2009, but continuously increased in other regions such as the Lower Valais. The warm late summer 2009 has then increased the running MAGST by 0.2 to 0.5 °C. A further increase resulted for the Northern Alps the following winter 2009/2010, whereas in the inner parts of the Alps a slight decrease can be observed. During the moderate summer 2010

Table 3.2: GST sites and start of the ground surface temperature measurements. T=temperature site, K=kinematics site, BTS=site with BTS measurements (see. Tab. 3.3). Brackets mark data not included in PERMOS, Reference Sites are marked in bold.

Site	Region/Valley	Since	T	K	BTS
Aget	Val de Bagnes, VS	1998		x	
Attelas	Val de Bagnes, VS	2001	x		
Alpage de Mille	Val de Bagnes, VS	1997		x	x
C. de la Lé-Sanetsch	Bernese Oberland, BE	1998			
Dreveneuse	Chablais, VS	2004	x		
Flüela	Lower Engadine, GR	2004	x		
Valle di Sceru	Valle di Blenio, TI	2006		x	
Gemmi-Furggentälti	Berner Oberland, BE	1994		x	
Lapires	Val de Nendaz, VS	1998	x	x	x
Monte Prosa	Gotthard, TI	2009		x	
Murtèl-Corvatsch	Upper Engadine, GR	2000	x	x	
Réchy	Val de Réchy, VS	1997		x	(x)
Schafberg	Upper Engadine, GR	2000	x		
Schilthorn	Bernese Oberland, BE	1999	x		
Tsarmine	Val d'Arolla, VS	2007		x	
Tsaté	Val d'Hérens, VS	2009	x		
Yettes Condjà	Val de Nendaz, VS	1998		x	(x)

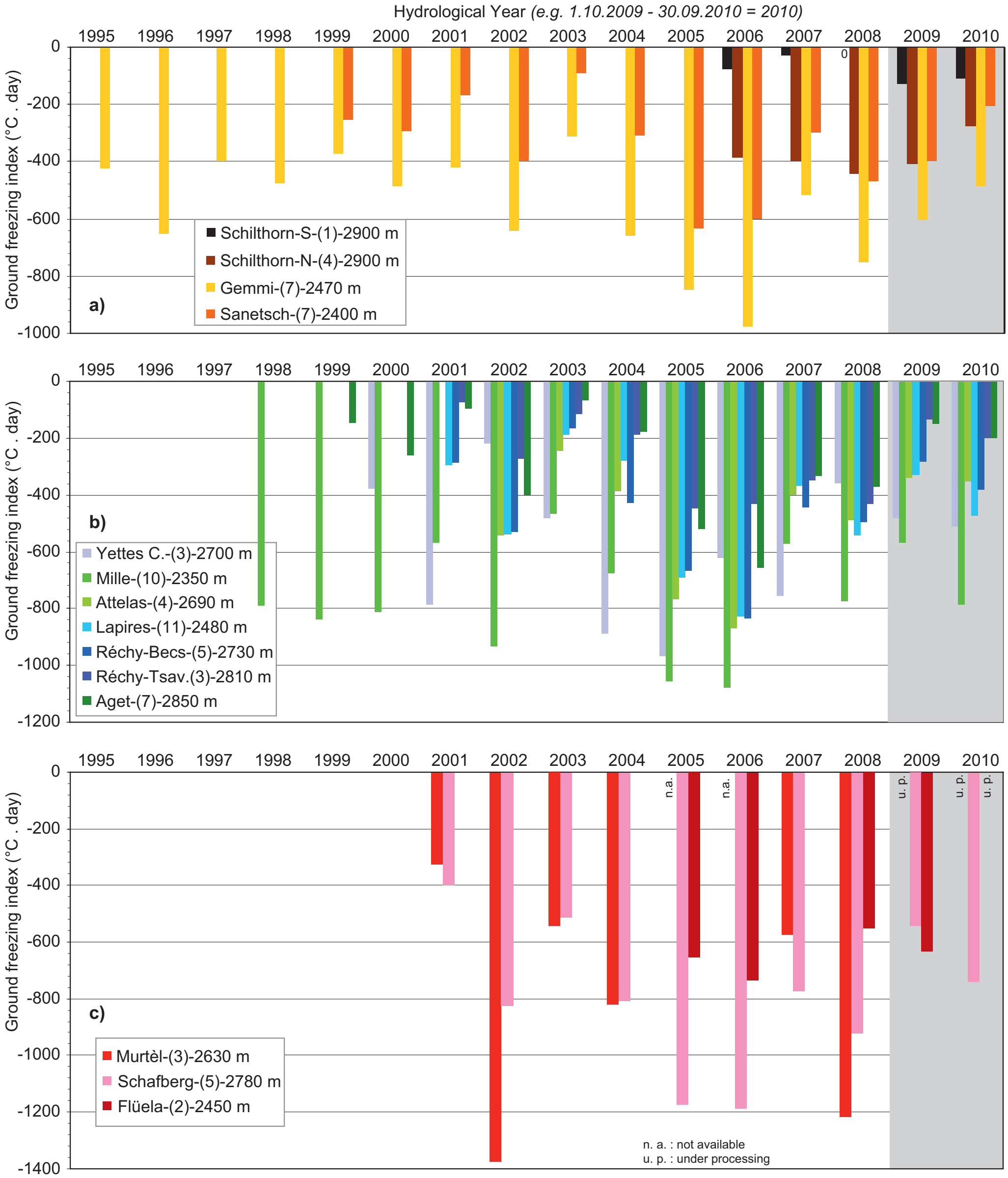


Figure 3.2: Ground freezing index (GFI) at the PERMOS GST sites: a) Bernese Oberland, b) Lower Valais, c) Engadine. Legend: site-(total number of sensors)-mean elevation.

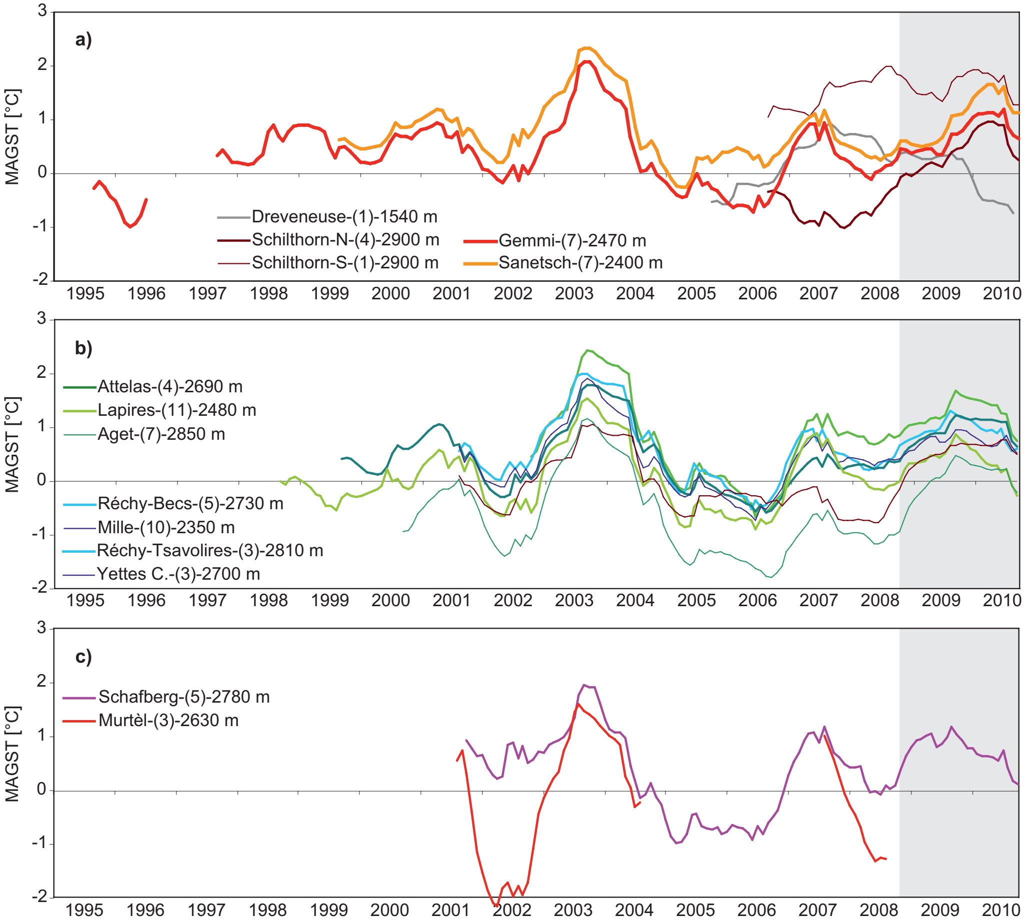


Figure 3.3: *Evolution of the mean annual ground surface temperature (MAGST): a) Bernese Oberland, b) Lower Valais, c) Engadine. MAGST is computed as running annual mean based on monthly aggregation, plottet at the end of the annual period used for the calculation. Legend: site-(total number of sensors)-mean elevation.*

Table 3.3: *Date of BTS measurements in 2009 and 2010.*

Site	Region	Available BTS	BTS 2009	BTS 2010
Alpage de Mille	Val de Bagnes, VS	since 1996	17.03	08.03
Lapires	Val de Nendaz, VS	since 2001	16.03	16.03

the running MAGST values decreased at all sites. In September 2009 (in the Valais Alps) and in July 2010 (in the Bernese Oberland) the highest MAGST values were measured since the record values in 2003.

In the lower part of ventilated talus slopes the ground surface thermal regime is particularly sensitive to winter temperature, independent of the snow conditions. In such a location, in the lower part of the Dreveneuse talus slope, the lowest GST were observed at the end of the reporting period. The site is located at 1540 m a.s.l. only, which is 850–1300 m lower than the other sites.

3.1.3 BTS

BTS mapping within PERMOS is performed to provide a snapshot on the thermal state of the ground in the second part of the winter season (usually in March). The ground surface temperature is assumed to be relatively stable at this time and to reflect the intensity of the cooling from the surface during winter. In winter 2009 and 2010 BTS measurements were continued at the two sites Lapires and Alpage de Mille (Tab. 3.3, Fig. 3.4). Results show a slightly higher mean BTS value in March 2009 than the mean observed so far and a snow depth 30–40 cm above average. In contrast, the BTS values measured in March 2010 were about 0.5 °C and the snow depth 5–20 cm below the average.

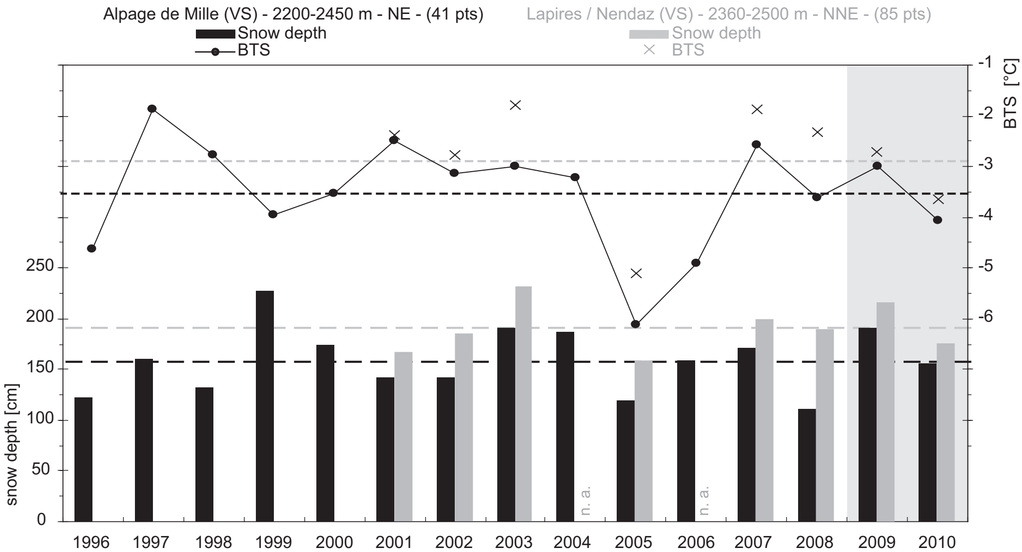


Figure 3.4: *Mean BTS and snow depth since 1996 on two sites in the Lower Valais. Dotted lines are the mean values for available BTS and snow depth time series at Alpage de Mille (1996–2010, black) and Lapires (2001–2010, grey).*

3.2 Borehole Measurements

The PERMOS Network 2010 includes 25 boreholes at 15 sites (see Fig. 1.1 and Tab. 3.4). Data are reported for the first time in this issue for the borehole Ritigraben 0102, which was included in the network in 2009, and the four permafrost boreholes drilled in summer 2008 in the talus slopes at Lapires and Les Attelas (Scapozza et al. 2011). A borehole outside of permafrost has also been installed at both sites, but the thermal conditions at these locations are strongly influenced by ventilation effects in the talus slopes and therefore not suitable for long-term monitoring of subsurface thermal conditions. The measurement installation of the first borehole on the rock glacier Corvatsch-Murtèl, which was installed in 1987, has been renovated in Summer 2009. The homogenization with the previous time series has been finished only for the thermistors in the upper part so far. The boreholes on the moving part of rock glacier Muragl have probably sheared off and the thermistor chains are broken. Only data from the boreholes Muragl 0199 and Muragl 0499 are available for the reporting period. The measurement station on Stockhorn was rebuilt in spring 2010 after a major storm in 2009.

3.2.1 Active Layer Thickness

The active layer thickness (ALT) in the year 2009 could be determined for 20 boreholes and for two boreholes there is a data gap in the respective period. The ALT in the year 2010 was determined for 18 boreholes and for four boreholes there is a data gap in summer. Three boreholes are not within permafrost and no active layer thickness is calculated: Dreveneuse 0104, Gemsstock 0106, and Muragl 0199.

ALT was higher in the reporting period than in the previous years and above the average of the first decade of PERMOS observations (Tab. 3.4, Fig. 3.5) in both summer seasons reported. ALT values for 2009 and 2010 at the different sites range between 0.99 m in the scree slope of Muot da Barba Peider and 7.18 m at the Schilthorn. Especially the hot period in summer and autumn 2009 has led to active layer thicknesses up to 50% higher than in the five years since the extreme summer 2003, when record values were documented at nearly all sites. A complete list of active layer thickness for all years and boreholes is provided in the Appendix (Tab. A.2).

3.2.2 Borehole Temperatures

Temperatures measured in the boreholes during the reporting period are depicted in Figures 3.6–3.7. The ground temperatures measured in 2009 and 2010 were relatively high compared to the previous years since 2003. Particularly, minimum ground temperatures at snow-rich sites such as Schilthorn, Schafberg, Gentianes or Corvatsch-Murtèl show an increasing trend and were at record values in 2010 as a result of the hot autumn 2009 and the early insulating winter snow cover. Temperatures at 10 m depth at the Flüela site remained above the freezing point for four years now (see Fig. A.6). In general, ground temperatures have been increasing during the reporting period and are again in the region of or even higher than in the extreme summer 2003.

Table 3.4: Maximum active layer thickness (ALT) measured in the boreholes and corresponding date for the years 2009 and 2010. «No AL» means that no active layer could be recorded because only seasonal freezing occurred at the borehole site; «n.a.» means that no data are available to calculate an ALT for this year.

Borehole	Region	Elev. (m a.s.l.)	ALT09 (m)	Date 2009	ALT10 (m)	Date 2010
Attelas 0108	Lower Valais	2657	3.93	06.09.	3.83	28.08.
Attelas 0208	Lower Valais	2689	5.75	30.08.	4.95	26.08.
Corvatsch-Murtèl 0287	Engadine	2670	3.54	08.09.	3.54	26.08.
Corvatsch-Murtèl 0100	Engadine	2670	2.48	03.09.	2.43	24.08.
Dreveneuse 0104	Chablais	1580	no AL	–	no AL	–
Flüela 0102	Engadine	2394	2.95	01.09.	2.94	29.08.
Gemsstock 0106	Urner Alps	2910	no AL	–	no AL	–
Gentianes 0102	Lower Valais	2895	12.14	02.10.	2.01	25.09.
Lapires 0198	Lower Valais	2500	45.26	19.10.	5.21	04.10.
Lapires 1108	Lower Valais	2500	4.87	08.10.	4.44	13.10.
Lapires 1208	Lower Valais	2500	n.a.	n.a.	4.08	27.08.
Matterhorn 0205	Upper Valais	3270	3.66	01.10.	2.98	03.09.
M. da Barba Peider 0196	Engadine	2946	10.99	28.09.	n.a.	n.a.
M. da Barba Peider 0296	Engadine	2941	2.02	04.10.	2.03	04.09.
Muragl 0199	Engadine	2536	no AL	–	no AL	–
Muragl 0499	Engadine	2549	4.48	20.08.	4.48	05.09.
Ritigraben 0102	Upper Valais	2600	4.20	08.10.	3.92	31.08.
Schafberg 0190	Engadine	2755	4.12	04.11.	n.a.	n.a.
Schafberg 0290	Engadine	2735	5.11	05.09.	5.10	03.09.
Schilthorn 5198	Bernese Oberland	2910	6.99	23.10.	6.80	20.09.
Schilthorn 5000	Bernese Oberland	2910	7.18	21.11.	n.a.	n.a.
Schilthorn 5200	Bernese Oberland	2910	2.96	01.11.	n.a.	n.a.
Stockhorn 6000	Upper Valais	3410	n.a.	n.a.	3.30	27.09.
Stockhorn 6100	Upper Valais	3410	4.44	28.11.	4.45	03.12.
Tsaté 0104	Lower Valais	3040	6.97	26.10.	6.80	06.10.

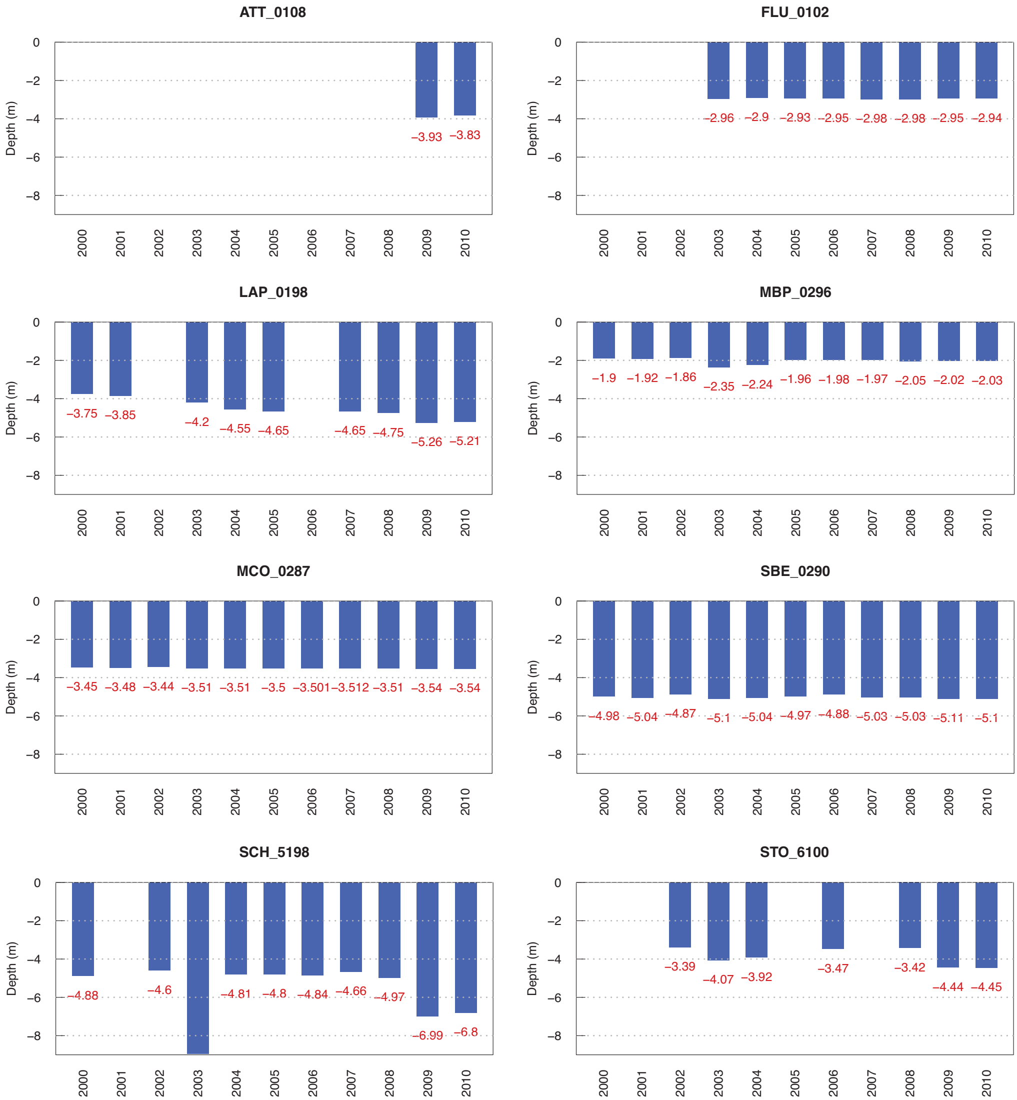


Figure 3.5: *Maximum active layer thickness measured at the PERMOS Reference Sites in the past 10 years: Les Attelas, Flüela, Lapires, Muot da Barba Peider, Corvatsch-Murtèl, Schafberg, Schilthorn, Stockhorn.*

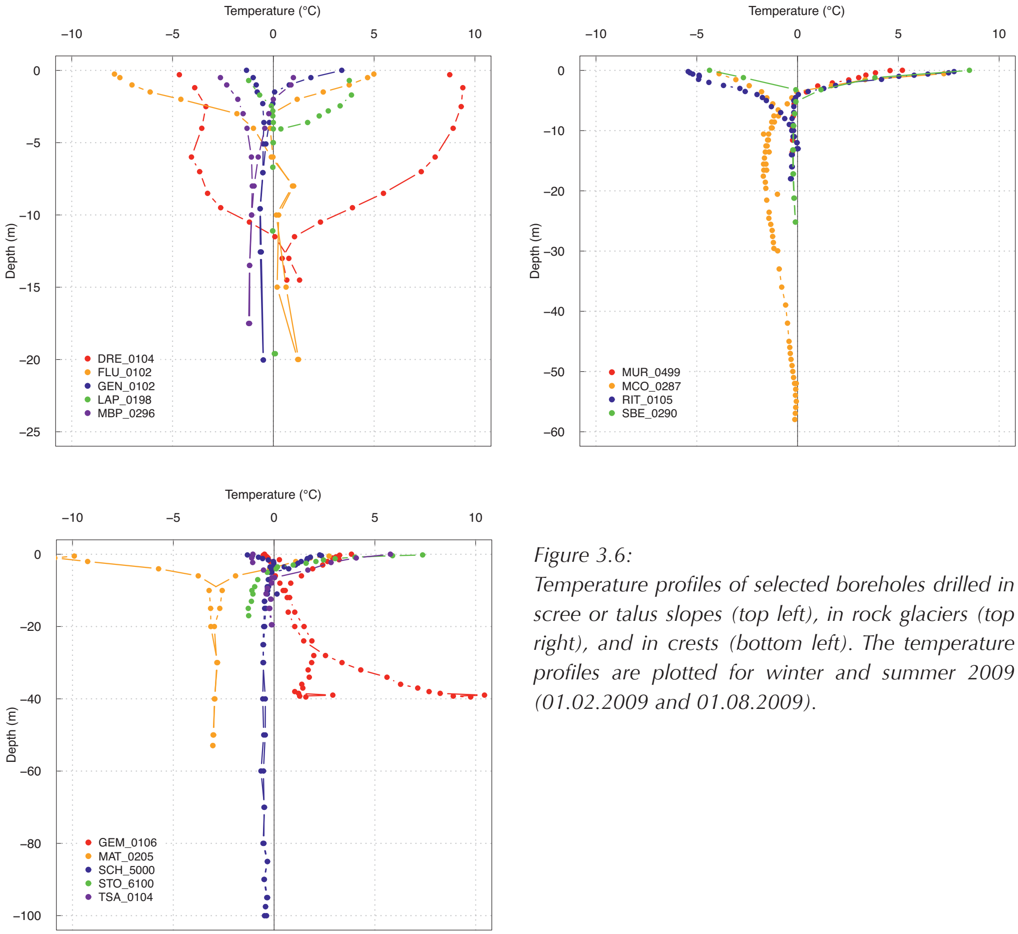


Figure 3.6:
Temperature profiles of selected boreholes drilled in scree or talus slopes (top left), in rock glaciers (top right), and in crests (bottom left). The temperature profiles are plotted for winter and summer 2009 (01.02.2009 and 01.08.2009).

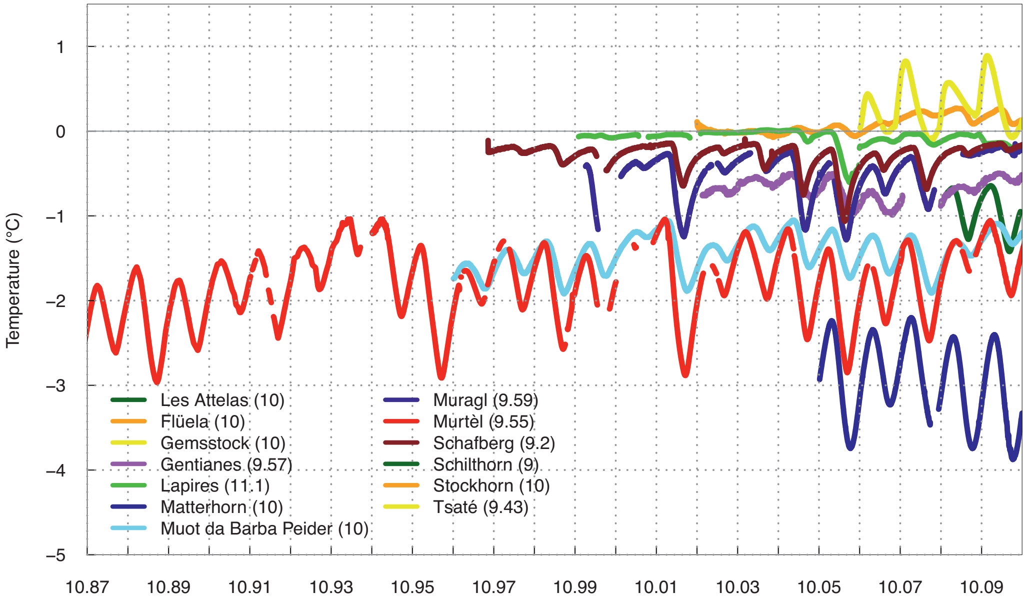


Figure 3.7: *Daily ground temperatures measured in selected PERMOS boreholes at ca. 10 m depth. For each borehole, the data measured at the thermistors closest to 10 m depth is plotted. The exact depth is indicated in brackets in the legend.*

3.3 Summary

GST measured at sites in bedrock and loose debris reflect the atmospheric conditions during the reporting period. Especially the warm late summer 2009 led to high ground surface temperatures in the range of the 2003 extreme values. In the moderate summer 2010 temperature conditions were cooler again. In general, surface temperatures were higher than during the previous reporting period.

After a 5-year period of more or less stable active layer thicknesses, values for both reporting years were significantly higher as a result of the warm summer conditions, especially in 2009. Similarly, the ground temperatures at about 10 m depth have been above the average of the previous years and particularly minimum ground temperatures at snow-rich sites were at record values for both years.

4 Electrical Resistivities

The four existing permanent two-dimensional electrical resistivity profiles at Schilthorn, Corvatsch-Murtèl, Lapires and Stockhorn have been complemented by two new ones: a vertical profile at Lapires talus slope (in addition to the horizontal one) and a vertical profile in the Flüela talus slope. The Flüela profile adds a second talus slope to the geoelectric monitoring and represents a site with a long tradition in permafrost research. Haeberli (1975) started first geophysical measurements here in the 1970s. All permanent ERT profiles are located close to the boreholes to characterise the drill site and to allow a joint analysis of the ground temperatures with the temporal changes in resistivities, the latter being indicative for changes in water and ice contents.

Table 4.1: Overview of all ERT sites. «# electr.» denotes the number or electrodes, «length» the length of the profile, «app-d» the approximate depth of investigation and «BH-dist horiz.» is the horizontal distance to the borehole(s).

ERT-Site	Location	# electr./ spacing (m)	length/ app-d (m)	BH–dist horiz. (m)	Since
Schilthorn (SCH)	horizontal in N-slope	30/2	58/10	5198: 11	Aug 99
				5000: 26	
Schilthorn (SCV)	vertical across crest (N-S)	47/4	184/30	5198: 20	Aug 06
Corvatsch-Murtèl (MT)	longitudinal along rock glacier	48/5	235/40	0287: 55	Aug 05
Stockhorn (ST)	N-S across plateau	55/2	108/15	6000: 28	
				61/00: 57	Sep 05
Lapires (LAH)	horizontal in N-slope	43/4	168/25	0198: 112	Aug 06
Lapires (LAV)	vertical in N-slope	70/4	276/25	0198: 108	
				1208: 188	
				1308: 264	Jun 07
Flüela (FL)	vertical in N-slope	50/4	196/30	0102: 36	Aug 09

4.1 ERT Results for 2008/2009 and 2009/2010

The Figures 4.1 and 4.3–4.6 (left panels) show selected tomograms for each site with results from measurements in August/September. The inter-annual changes in resistivities are calculated to obtain information related to changes in permafrost (right panels of Figs 4.1 and 4.3–4.6). These can in principle be related to changes in ice and unfrozen water content due to thawing or freezing processes. A resistivity decrease (red colours) may thus point to an increase in unfrozen water content and/or a decrease in ice content, and a resistivity increase (blue colours) may be caused by ice aggradation and/or drained pore water.

The Schilthorn has been recognised as a very sensitive site to interannual changes in weather conditions during the hot summer 2003 when the active layer depth almost doubled (Hilbich et al., 2008, 2011, PERMOS 2007).

The quite warm years 2009 and 2010 show again a remarkable impact on the resistivities in both profiles (cf. Fig. 4.1 and Fig. 4.2): Values were significantly lower in both years and even fell below the values of summer 2003, marking a new record. Correspondingly, borehole temperatures at Schilthorn show rather high temperatures for 2009 and 2010 (cf. Chapter 3.2). Also the active layer was deeper than normal, but still did not reach the record from 2003 (cf. Fig. 3.5). The significantly decreasing resistivities in the top part of the cross-crest profile (Fig. 4.1, right panel) are unfortunately «contaminated» by metal structures from an old cable car and other installations around the Schilthorn crest and the interpretation of a potential permafrost signal is complicated.

The tomograms from Stockhorn are of limited comparability regarding inter-annual changes because the measurements since 2005 were performed in different months. The resistivity changes between 2005 and 2010 (Fig. 4.3 right) may therefore reflect seasonal signals (e.g., thawing of the active layer or advance of the warming front in summer) rather than annual changes of the permafrost conditions. However, the predominantly decreasing resistivities in 2010 compared to 2008 (lowermost panel in Fig. 4.3 right) are in good correspondence with significantly deeper active layer in 2009 and 2010 compared to the years before (cf. Chapter 3). The impact seems to be even stronger in between the two boreholes – a zone which is interpreted to contain more porous material (more intensely weathered bedrock and/or more sediment cover) than directly at the boreholes.

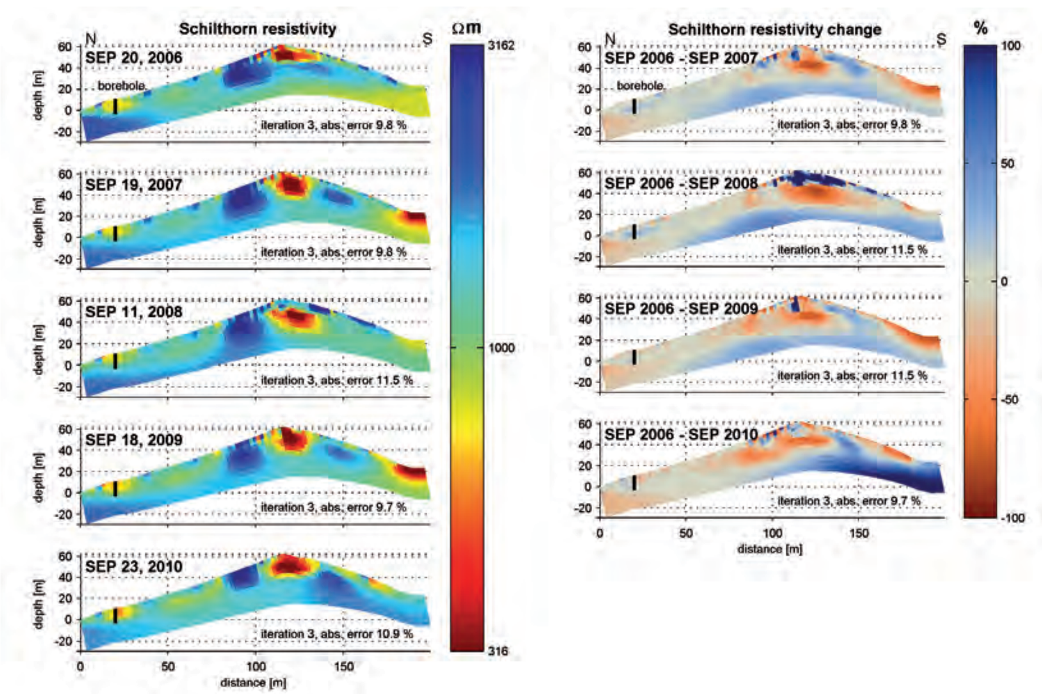


Figure 4.1: *Tomograms with resistivity distribution (left) and time-lapse tomograms with the resistivity change (right) for the years 2006–2010 of the vertical profile across the Schilthorn crest (SCV).*

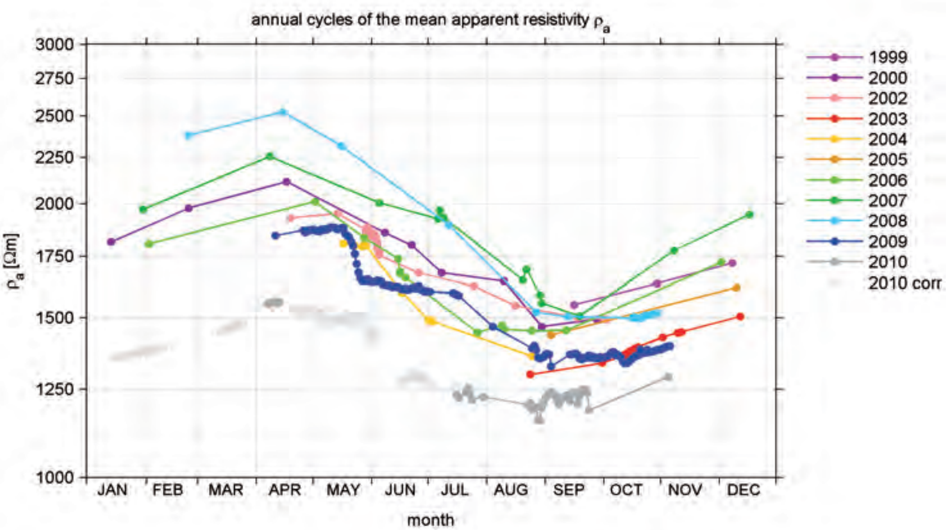


Figure 4.2: *Annual cycles of average apparent resistivities (ρa) 1999–2010 for the horizontal ERT profile on Schilthorn (SCH). Many values in 2010 (open grey circles) had to be corrected for a linear shift due to a technical problem with the instrument.*

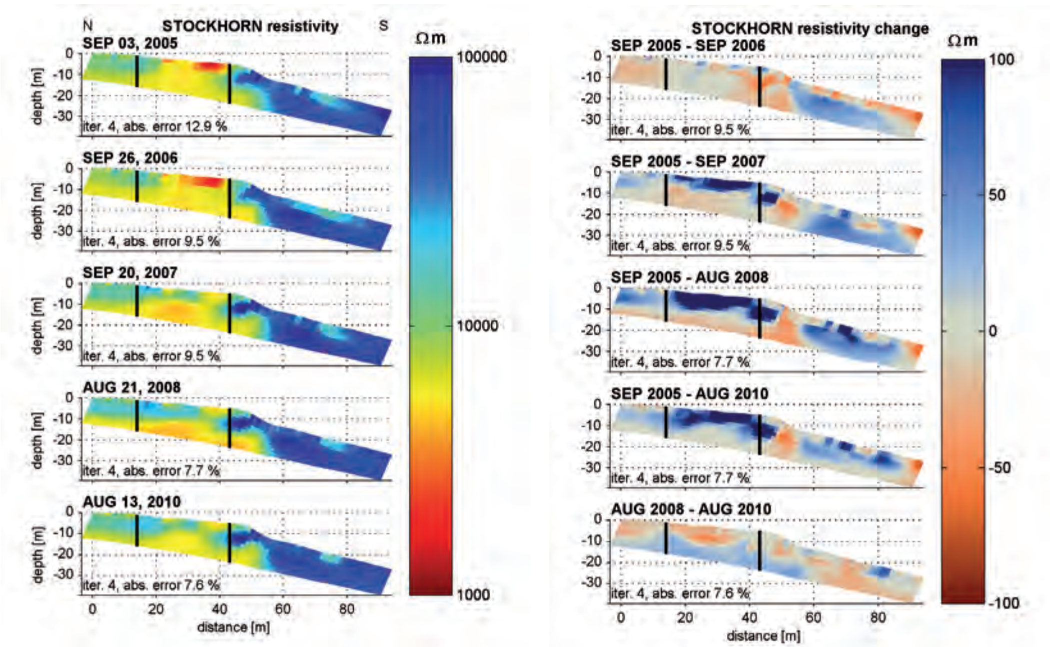


Figure 4.3: *Tomograms with resistivity distribution (left) and time-lapse tomograms with the resistivity change (right) for the years 2005–2010 of the profile across the Stockhorn plateau (ST).*

The vertical ERT profile in the Lapires talus slope was installed in 2008 and represents a longitudinal section through the frozen part of the talus slope (blue zone in Fig. 4.4 left). The internal ventilation makes talus slopes highly dynamic systems, which may react much faster to changes in external forces than unventilated underground. But the combination of advective and conductive heat transfer processes is complex and cannot easily be interpreted in terms of warming-induced thawing or cooling-induced freezing only. Fig. 4.4 (left) shows a significant change both in the outline and the absolute resistivity values of the blue zone representing the permafrost body. Consequently, the resistivity changes 2008–2010 (Fig. 4.4 right) are relatively strong. For a reliable interpretation however longer time series are needed.

For the first two years of ERT monitoring at the Flüela site the resistivity decrease below 5 m depth is consistent with the borehole temperatures, which show a strong temperature increase at this depth since 2004 (Fig. 4.5, Phillips et al. 2009). The resistivity increase in the small ice body in the lowermost part of the profile may be a true feature but may also be an inversion artefact due to the resistivity decrease nearby.

The rock glacier Corvatsch-Murtèl is the landform with the highest overall resistivity values in the ERT network. As shown in Hilbich et al. (2009), resistivity changes in such resistive material have to be treated and interpreted with great care, because the strong resistivity contrast between the active layer and the ice body makes it necessary to prevent the interpretation of inversion artefacts. In general, only resistivity changes in the uppermost few metres are reliable. Compared to the resistivity changes in previous years, changes in 2009 and 2010 were rather small with a slight tendency to lower resistivities in 2010.

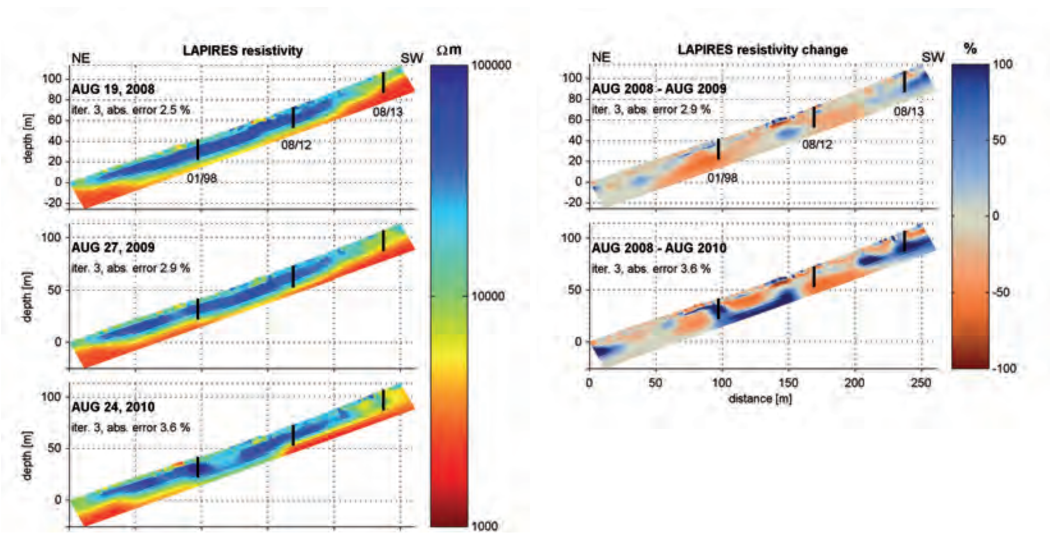


Figure 4.4: *Figure 4.4: Tomograms with resistivity distribution (left) and time-lapse tomograms with the temporal resistivity change (right) for the years 2008–2010 of the vertical profile in the Lapires talus slope (LAV).*

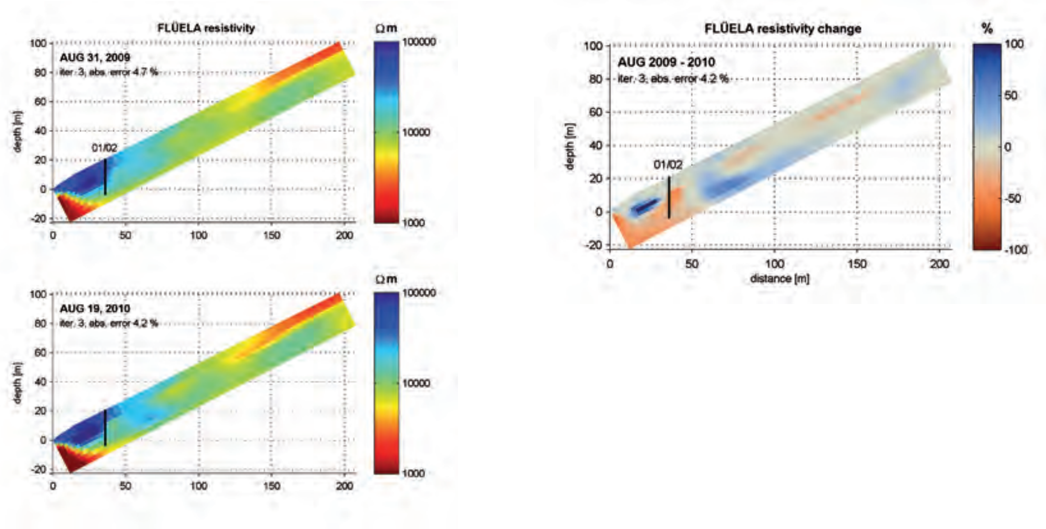


Figure 4.5: Figure 4.5: Tomograms with resistivity distribution (left) and time-lapse tomograms with the resistivity change (right) for the years 2009–2010 of the vertical profile at the Flüela site (FL).

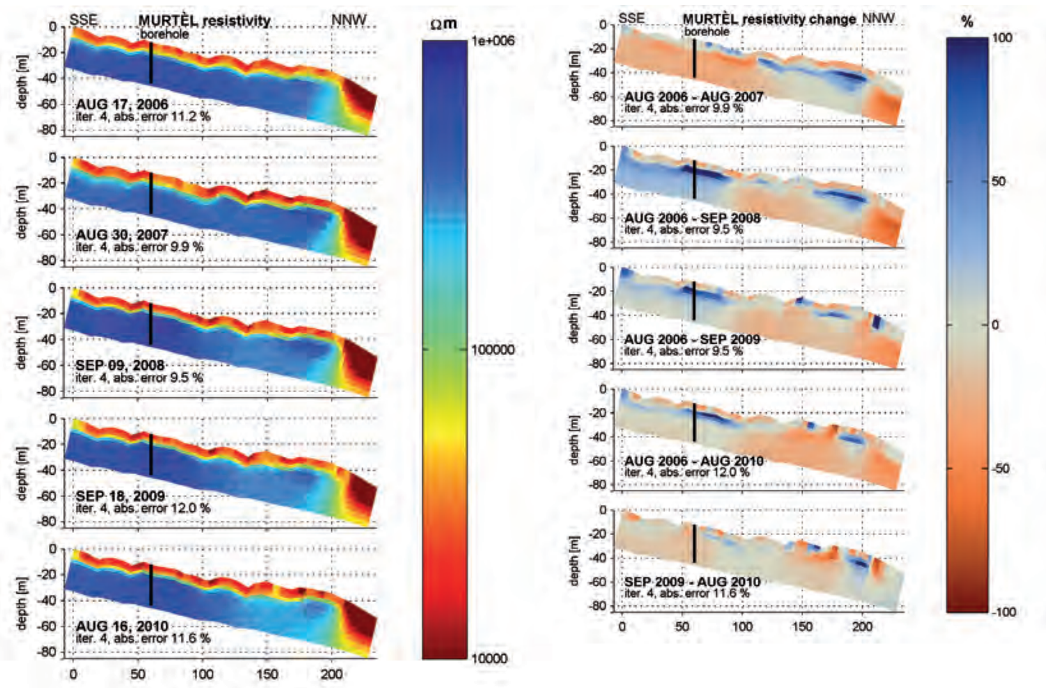


Figure 4.6: Tomograms with resistivity distribution (left) and time-lapse tomograms with the temporal resistivity change (right) for the years 2006–2010 of the longitudinal profile across the frontal part of the Corvatsch-Murtèl rock glacier (MT).

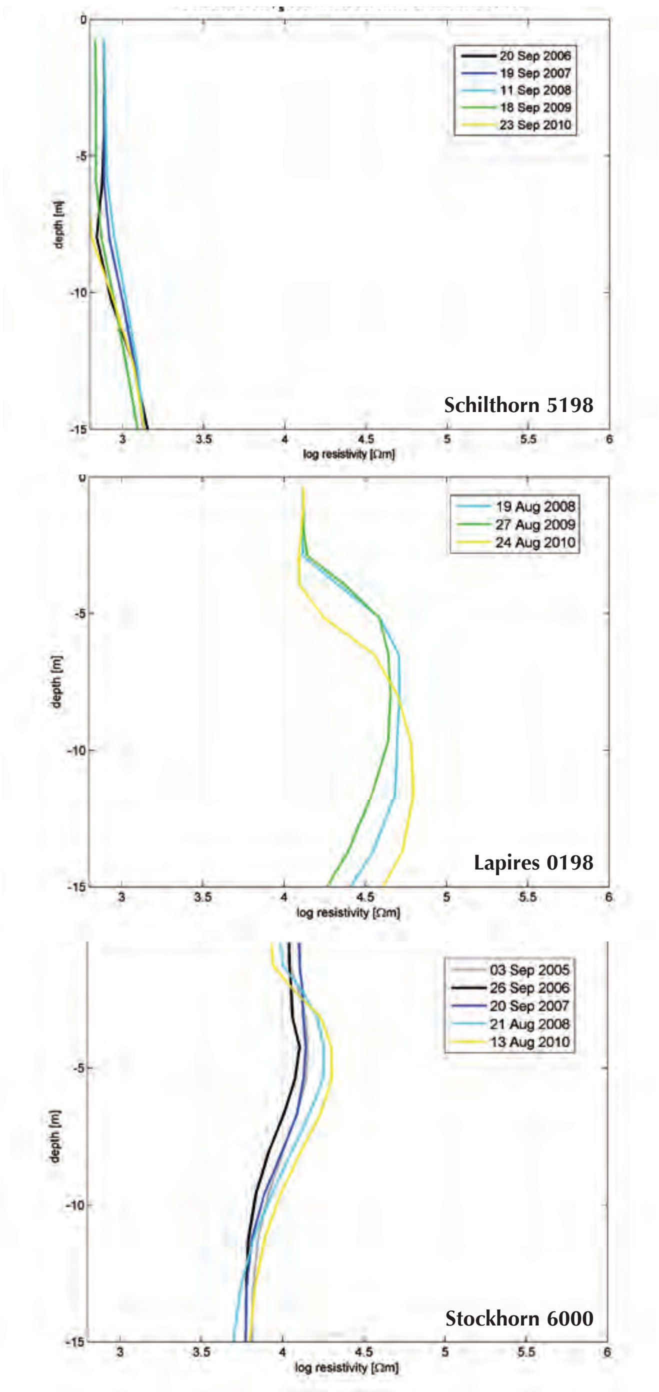
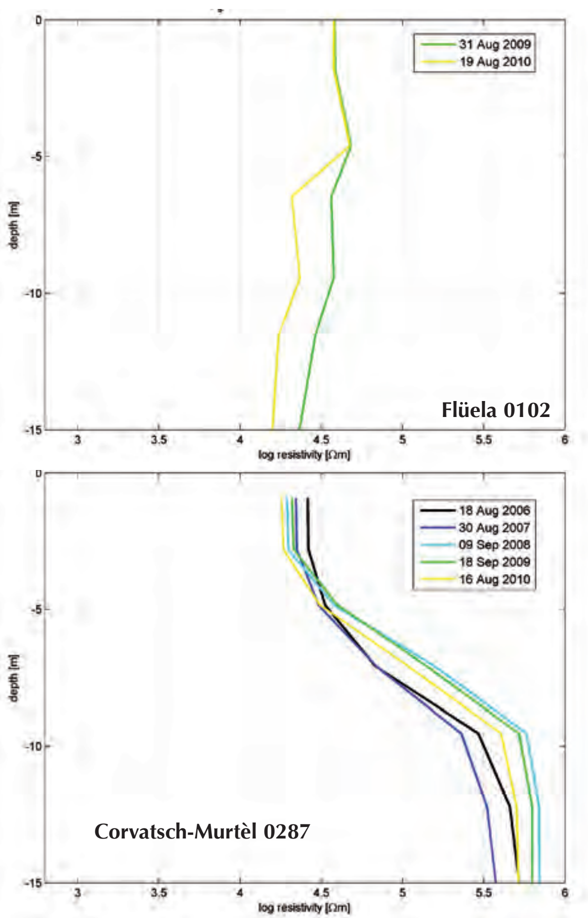


Figure 4.7: Depth profiles of the specific electrical resistivity (ρs) shown as virtual boreholes through the ERT tomograms at the position of the (true) PERMOS boreholes. (Figure continues on next page).



4.2 Summary

Schilthorn is the only site with a clear signal that indicates an evolution in the resistivity measurements in the period 2008–2010. The measurements in 2009 and 2010 show the lowest values since the begin of ERT monitoring in 1999. This is attributed to a cumulative effect of the two rather warm years 2009 and 2010, which is also visible in the borehole temperatures and active layer depths. With its thermal regime very close to the freezing point and an active layer depth between 5 and 9 m, the Schilthorn has long been recognized as a site that is particularly sensitive to interannual changes in atmospheric parameters (Hilbich et al. 2008). Increased active layer depths in 2009 and 2010 compared to previous years were observed at all ERT monitoring sites, except for the Flüela site (cf. chapter 3). This increase corresponds with slightly lower resistivities at these sites compared to previous years.

Photo 1: Drilling of three new boreholes in the talus slope of Lapires, Valais Alps, in October 2008. Photo: Cristian Scapozza.

5 Kinematics

Rock glaciers are key landforms in high mountain permafrost and their movements reveal information on subsurface processes such as temperature conditions, ice content and unfrozen water fluxes and their respective changes. Continuous long-term data series of permafrost creep are recorded at 14 rock glaciers within PERMOS in order to provide a basis for the understanding and investigation of ongoing processes and dynamics.

In addition to the already established aerial surveys, terrestrial geodetic surveys (total station or differential GPS) were carried out at several PERMOS sites for several years and implemented as a PERMOS observation element for a two-year pilot phase 2008–2010 (PERMOS 2009, 2010). This was decided due to the detection of significant seasonal, interannual and long-term variations in rock glacier kinematics (Delaloye et al. 2010, PERMOS 2009), and in order to increase the temporal resolution by repeated annual and seasonal measurements. The aim is to analyse geometry changes (i.e., horizontal velocities and vertical changes) in more detail and to differentiate normal creep processes from permafrost degradation phenomena (e.g., vertical thinning due to ice melt, rock glacier acceleration). Terrestrial geodetic surveys were officially included in the PERMOS monitoring strategy following the pilot phase 2008–2010. Permafrost creep is now monitored by quantifying decadal, annual as well as seasonal movements using a combination of remote sensing and in-situ measurements.

5.1 Monitoring Strategy

Special aerial photographs taken every 5–7 years from low flying altitudes (scale about 1:6000) are obtained to monitor different rock glacier sites in different regions of the Swiss Alps since the beginning of operational monitoring in 2000. Digital terrain models (DTM's) as well as orthophotos are compiled in order to describe and quantify horizontal velocities and vertical changes for the entire landform on a decadal scale. That way, vertical changes can be determined independently of the horizontal displacement.

Terrestrial geodetic surveys to obtain annual and interannual changes are performed at a selected number of PERMOS sites and included in the monitoring strategy since 2008. Measurements are repeated at least annually at approximately the same date (in late summer) and at an approximate number of 20 points (blocks) per hectare. Horizontal (Δxy) and vertical (Δz, ratio of slope) changes are quantified based on coordinates (x, y) and altitude (z) with a resolution of 1–2 cm. The analysis of the data includes flow fields, spatio-temporal variations, mean values (all data points) and reference values (depending on morphology, flow pattern and specific characteristics of the landform, see for example Fig. 5.1). The terrestrial geodetic surveys are performed either using a total station or a differential GPS with a high temporal resolution (seasonal and annual) for a number of selected blocks on each rock glacier (10–100 points, depending on feasibility). Most of the observation sites were established within scientific projects and have been observed for several years up to a decade (Tabs. 5.1 and 5.2). GST are also measured at several points on the monitored rock glaciers and a permanent ERT profile is installed at some sites in order to analyze the correlation of permafrost creep processes with ground temperatures and changes in ice content (see Tab. 1.1).

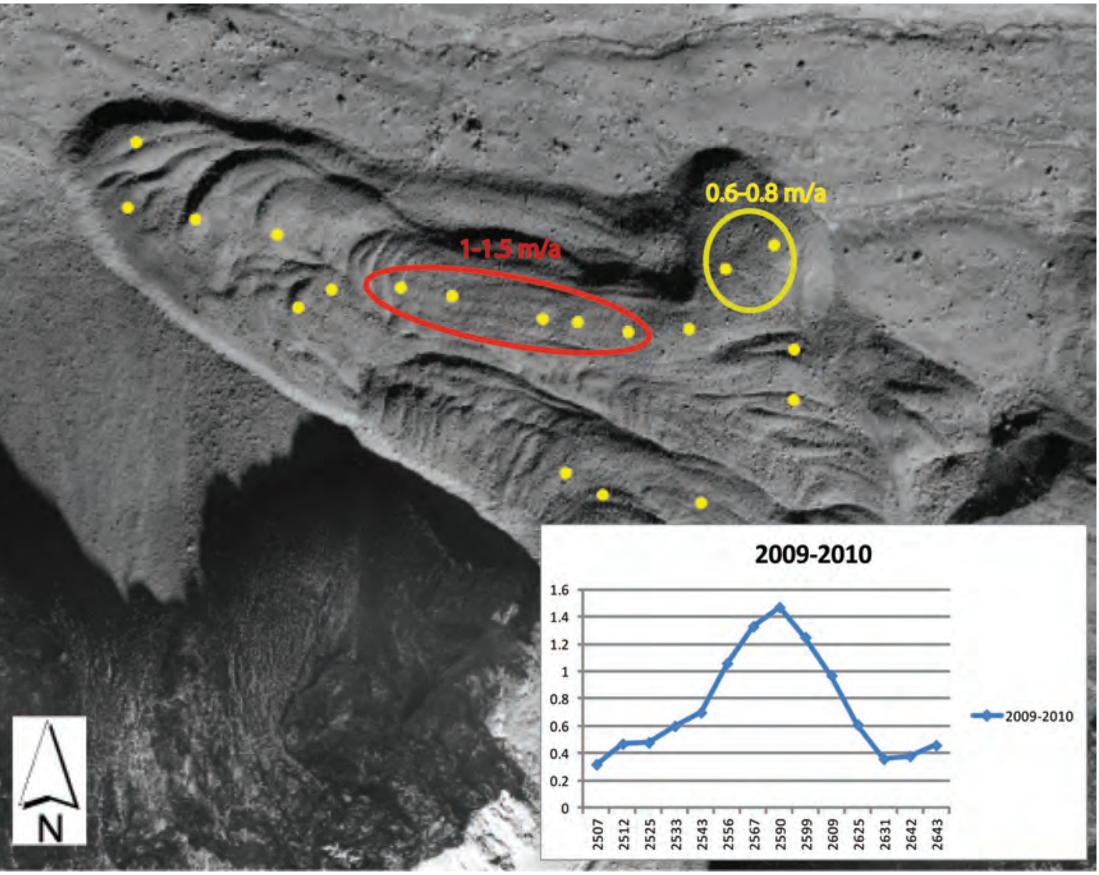


Figure 5.1: *Muragl (Engadine): network of terrestrial survey (yellow dots) and highest horizontal velocities on the central lobe and the small «outbreaking» lobe between 26.08.2009 and 26.08.2010. The inserted graph shows the horizontal velocities of selected blocks on a profile line from the front to the rooting zone. Underlying orthophoto from 2007 (© Swiss Federal Office of Topography (Swisstopo), processed by I. Gärtner-Roer and P. Thee.*

In addition to the slow processes as in rock glaciers, rock fall events in permafrost environments are also documented. Kinematics are not possible to be measured here, but information such as the date of the event, location of the starting zone, volume, or geological characteristics is collected to build a basis for future analyses.

5.2 Permafrost Creep

During the reporting period 2008/2009 and 2009/2010 aerial photographs were taken at the two sites Gruben (2008, 2010) and Gemmi rock glacier (2010, cf. Tab. A.5).

Terrestrial surveys were extended and are now conducted at 15 rock glaciers (cf. Tabs. 1.1 and A.4). Results are displayed in Tables 5.1 and 5.2. The monitoring sites in the Engadine and Ticino are not yet shown because the measurements only have started in 2009. The terrestrial survey 2009–2010 at Muragl rock glacier in the Engadine indicated horizontal velocities between 0.3 and 1.5 m a^{-1}. Highest velocities occurred in the central part of the rock glacier while velocities were significantly smaller at the front as well as on the «outbraking» lobe on the orographic right side (see Fig. 5.1). In general, ceep velocities dropped until 2006 after the extraordinary high horizontal velocities in 2003 and 2004. But starting in 2007 most of the sites show again increasing values (cf. Tabs. 5.1 and 5.2, Fig 5.2a). While the relative changes in horizontal velocities show large variations between 2001 and 2005, the changes are smaller in recent years (Fig 5.2b).

Table 5.1: Mean annual horizontal surface velocity in m a^{-1} (rounded to cm) of Kinematics Sites with terrestrial survey for the period 2004–2010. «num» indicates the number of measured points. Values marked with an asterisk are valid for two years.

Site (num)	01/02	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10
Aget (27)	0.15*	0.15*	0.2	0.15	0.10	0.09	0.12	0.12	0.13
Gemmi (18)	1.77	1.72	2.95	2.10	1.29	1.42	1.51	1.73	2.11
Grosses Gufer (15)							1.65	2.68	2.60
HuHH3 (22)		1.05	1.37	1.33	0.68	0.66	0.73	1.22	1.08
Lapires (8)							0.37	0.53	0.68
Réchy (6)			0.92	0.92	0.61	0.72	0.73	0.87	0.97
Tsarmine (23)				1.27	0.80	0.92	1.21	1.81	1.38
Yettes Condjà-B (12)	1.01*	1.01*	1.87	0.90	0.39	0.44	0.53	0.77	0.75
Yettes Condjà-C (19)	0.14*	0.14*	0.17	0.09	0.08	0.08	0.08	0.14	0.10

Table 5.2: Relative change of the mean horizontal surface velocity (reference values) of PERMOS rock glaciers (comparison to the respective previous year).

Site	01/02	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10
Aget			+35%	–25%	–36%	–2%	+24%	+6%	+5%
Gemmi	–7%	54%	+8%	–29%	–39%	+10%	+6%	+15%	+22%
Grosses Gufer								+62%	–3%
HuHH3			+30%	–3%	–49%	–3%	+11%	+67%	–11%
Lapires								+45%	+29%
Réchy				0%	–34%	+18%	+2%	+19%	+12%
Tsarmine					–37%	+16%	+31%	+50%	–24%
Yettes Condjà-B	+9%*	–	+85%	–52%	–57%	+14%	+21%	+44%	–2%
Yettes Condjà-C	+49%*	–	+23%	–48%	–4%	–11%	+12%	+62%	–29%
Average			+36%	–26%	–36%	+6%	+15%	+41%	0%

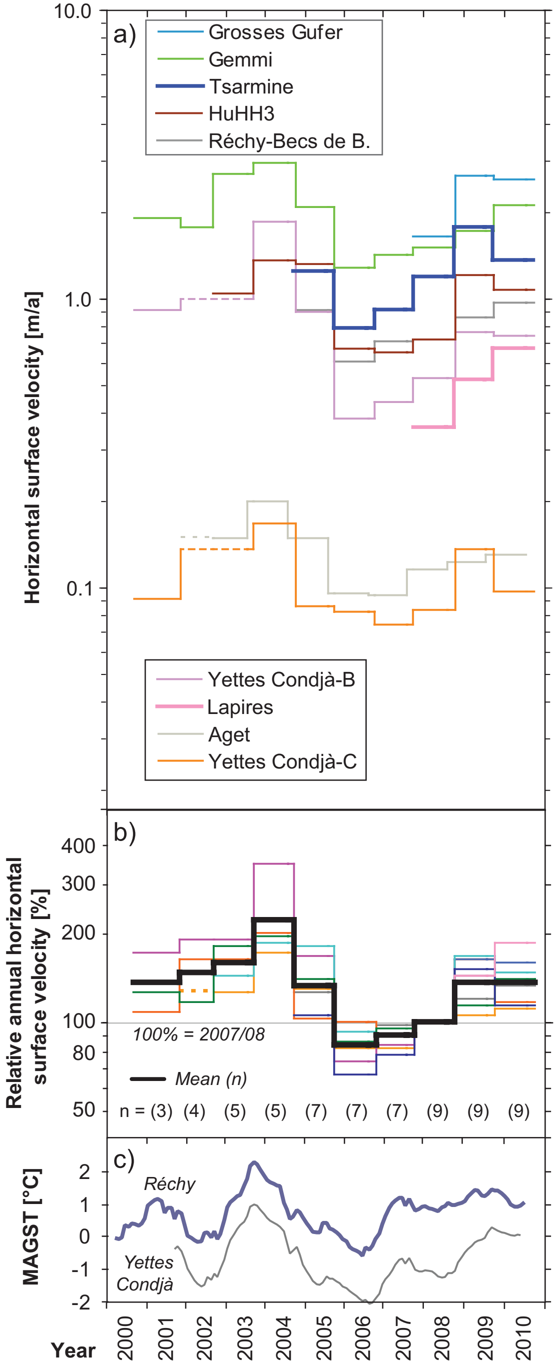


Figure 5.2:
Horizontal velocities (reference values) of eight sites in Valais between 2000 and 2008 derived from terrestrial surveys: a) horizontal velocities (m/a) and b) relative annual horizontal velocities (%) are linked to c) MAGST.

5.3 Rock Fall from Permafrost Area

A documentation for rock fall events with their starting zones in permafrost area was established for PERMOS in the scope of a Masters thesis at the UZH and in collaboration with SLF, the Federal Office for the Environment (FOEN), MeteoSwiss, and the Swiss Mountain Guide Association (SBV). The data is integrated when reported to PERMOS and not actively collected. Therefore the documentation does not provide a complete inventory but provides data for future analyses of rock fall starting zones, e.g., within a scientific study such as recently published by Fischer et al. (2012).

Basic information for nine events has been collected in the observation period from October 2008 to September 2010. They were located at an elevation between ca. 2700 and 4050 m a.s.l. (Tab. 5.3). At the Ritzlihorn in the Grimsel area, in 2009 and 2010 many smaller and larger rock falls detached from the North face at ca. 3000 m a.s.l. The major events occurred in July and August 2010. The deposits have been mobilised and transported down the valley by debris flows in summer 2010.

Table 5.3: Summary of the rock fall events which occurred in the reporting period and are contained in the documentation. Ice indicates whether it is known that ice was visible in the starting zone after the event.

Location	Description	Date	Elevation (m a.s.l.)	Aspect	Volume (m^3)
Besso		July 2009	3200	N	n.a.
Weisshorn	South face	19.08.2009	4050	SSE	n.a.
Zervreilahorn	NE ridge	30.09.2009	ca. 2800	N	>1000
Grabenhorn	Above Festigletscher	09.09.2009	3440	N	n.a.
Orny	Le Portalet	Spring 2009	3000	SE	ca. 4000
Ritzlihorn	N face	08.2009	ca. 3000	N	n.a.
Tödi	Gelbe Wand	2009	2700	ENE	ca. 1000
Egginer		Summer 2009		NW	
Ritzlihorn	N face	07/08.2010	ca. 3000	N	ca. 35'000
Monte Rosa East Face		26.09.2010	ca. 3100	ESE	n1000

5.3 Summary

The combination of remote sensing and in-situ measurements allows for the quantification of permafrost creep parameters on various temporal scales. The benefit of the analysis of repeated aerial images is the availability of data for the entire landform, including movement patterns. In addition, vertical changes are quantified independently of the downslope movement and changes related to ice melt or aggradation can be observed. In contrast, by the application of terrestrial methods, annual and seasonal changes can be described and interpreted.

Most of the aerial data have been processed and analyzed. The terrestrial survey was extended during the reporting period and long-term data (five years in series) is now available for six sites. After the extraordinarily high horizontal velocities in 2003 and 2004, the velocities dropped until 2006 and starting in 2007, most of the sites show a small increase. While the relative changes in horizontal velocities show large variations between 2001 and 2005, the changes have been much smaller in recent years.

Nine rock fall events with a volume of at least 1000 m^3 and at an elevation between 2700 and more than 4000 m a.s.l. have been documented in the permafrost areas of the Swiss Alps during the reporting period.

Photo 2: Rock glacier in the Hungerlitälli, Turtmanntal (VS). Photo: Johann Müller.

6 Selected Focus Topic

This chapter is reserved for the presentation of a selected focus topic of current permafrost research or new monitoring approaches from the PERMOS Partners. In this issue, we report on two exceptionally fast moving rock glaciers in the Valais: A fast moving rock glacier near the Furggwanghorn in the Turtmann valley is investigated within a new interdisciplinary research project and a number of boreholes were drilled in order to analyse the coupled thermo-hydro-mechanical processes. The second rock glacier is located on an extremely steep slope in the Matter valley above Randa and the fast creep has repeatedly led to problems, e.g., for the hiking trail «Europaweg». Here, the fast movements are predominantly a result of a cascading reaction from the rooting zone to the front of the rock glacier during several decades.

6.1 Preliminary Results from a Fast Moving Rock Glacier Near the Furggwanghorn

Scientific and societal interest in permafrost and rock glacier degradation in Alpine permafrost is rising, given reported cases of large deformations combined with instabilities within rock glaciers attributed to thawing ice (Val Pola Italy, 1987, Crosta et al. 2006 and Bérard Rock glacier, Krysiecki et al. 2008). The creep behaviour of 30 rock glaciers was investigated in the Turtmann valley (Roer et al. 2005a&b, Kääb et al. 2006) between 1975 and 2001. Several exhibited significant creep behaviour during the period between 1993 and 2001. Two rock glaciers were selected for detailed study using aerial photographs from 1975, 1981, 1987 and 1999 and a clear correlation was demonstrated between air temperature increase and accelerated flow of the rock glaciers (Roer et al. 2005b; Kääb et al. 2007).

An interdisciplinary research project was started by the three ETH institutes, Geotechnics (IGT, leading house), Geophysics (IG) and Environmental Engineering (IfU) in early summer 2010. The aim was to characterise and monitor one of these rock glaciers, which is located between 2755 m and 2895 m a.s.l., below and to the west of the Furggwanghorn peak in the Turtmann valley (Upper Valais). It was postulated that the rock glacier surface can be divided into two different zones: a thermally degrading zone (TDZ) and an acceleration zone (AZ). The TDZ is characterised by the growth of two deep depressions (approximately to 14 m depth) over the last 20 years (Roer et al. 2008). The main goal of the interdisciplinary approach is to develop a deeper understanding of the coupled Thermal-Hydro-Mechanical (THM) processes taking place within the rock glacier. Currently, THM models are not well developed and the coupled processes affecting the mechanisms that influence creep response in the frozen soil have not been fully identified.

A portable drill rig was used to drill five boreholes named F1–F5 with rotary/percussion techniques at a diameter of 139 mm to a depth of 25 m (single tube technique). Their locations were determined from geophysical investigations (Notivol Lazaro 2011; Springman et al. 2011). A steel casing was used to avoid a collapse of the borehole walls during the drilling. As expected, the ground was extremely inhomogeneous. Layers of silty-clay sized particles alternated with gravel and large blocks. Permafrost conditions were also encountered. Thermistor chains, each with 30 sensors, were installed in boreholes F1–F4 to measure temperature at different depths. The sensors in the top 5 metres are located every 0.5 m, increasing to a spacing of 1 m below 5 m depth. Addition-

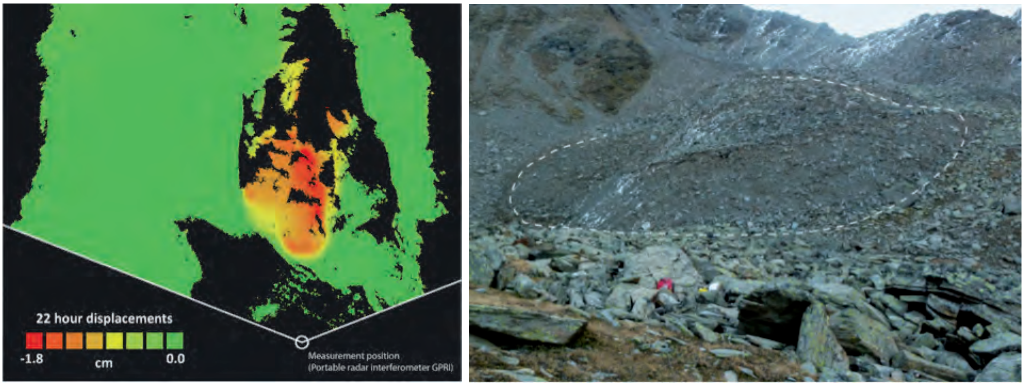


Figure 6.1: Preliminary radar results for a 22 hour measurement campaign. The radar was placed directly in front of the Furggwanghorn rock glacier (modified after Springman et al. 2012).

ally, 10 thermistors were placed on, or slightly below, the surface to determine ground temperatures around each borehole.

An inclinometer was installed in borehole F5 to obtain information about the downslope creep rate and to determine the depth of possible shear horizons. The inclinometer consisted of 48 rigid poles, 0.5 m in lengths, which are connected with joints that allow free rotation, but no extension. Each section contains accelerometers, which measure the inclination in two directions, and can be integrated over the instrument length to determine the net displacement profile and direction. Automatic inplace inclinometers have the advantage that data can be logged at specified time intervals, independent from snow height on the surface and other on-site weather conditions, which could prevent safe access for manual measurements. The inclinometer was expected to break after a few months because of the large displacements taking place on the rock glacier. Despite this, measurements have now been recorded for more than nine months.

A well-equipped weather station was placed on the rock glacier, in addition to the measuring instruments in the ground, to collect data about air temperature, humidity, precipitation, snow height, wind and radiation. All data are stored on site, since there is no mobile phone connection in the vicinity of the rock glacier. A solar charged battery powers the instruments and the logger station.

Two new boreholes (F6/F7) were drilled in late summer 2011. A thermistor chain and an inclinometer were installed in each borehole to measure temperature and displacement at the same location. The boreholes were located between 75 m and 100 m downslope of the previous boreholes in the designated AZ. Both boreholes were drilled using a mixture of rotary and percussion techniques. Disturbed samples were taken in borehole F7 using a sampling tube. Ideally, the rotary drilling bit should be cooled to prevent temperature increase due to friction and combined with triple tube sampling (Arenson 2002), however this was not feasible, and water flushing was used as an alternative. Grain size distributions of the samples recovered are currently being analysed. The in situ soil response was also investigated through pressuremeter tests (in both F6/F7) to determine the stiffness of the soil at several depths. All information was used to create a soil ground model of the rock glacier.

Measurements and observation in the field since summer 2010 confirmed the recent past creep activity of the rock glacier was quite complex, so the observation of the rock glacier's surface displacements was intensified. Stationary as well as mobile measuring systems will be used for this purpose. Furthermore, a portable imaging radar interferometer (GPRI) was used in September 2011 to measure surface displacements. The antenna of the radar system rotates across azimuth and displacement measurements of the surface were made along the radar line of sight at five minute intervals. Preliminary results (Fig. 6.1), show 1.8 cm of displacement during a 22 hour measurement campaign. A ground based LiDAR system was used for additional surface measurements. Both instruments will be used in tandem in 2012. Additionally, five GPS stations will be installed on each five boreholes in early spring 2012 to observe continuous displacements on the rock glacier surface.

Comprehensive monitoring of the rock glacier is essential for permafrost research, firstly to obtain a better understanding of the processes taking place within a rock glacier, and secondly to use field results to model the observed behaviour. Subsequent transfer into a monitoring network such as PERMOS is advisable in the future. First results are published in Buchli et al. (2013).

Photo 3: *View onto rock glacier at Furggwanghorn during the drilling campaign. Photo: Sarah Springman.*

6.2 The Extraordinary Destabilization of the Grabengufer Rock Glacier

The surface velocities of the Grabengufer rock glacier reached exceptionally high values of 100–150 m per year during summer and autumn 2009. For example at the front local velocities were even higher. The phase during with such of extreme creep velocities however began at least two decades earlier. In 2009 survey of the Grabengufer rock glacier and its source area were initiated by the Canton of Valais (Service for the Forests and Landscape, Natural Hazard section) and the local authorities (municipalities of St. Niklaus and Randa) and carried out by the Geography Unit of the University of Fribourg (Alpine Cryosphere and Geomorphology Group) in collaboration with private companies (Aufdenblatten Geomatik, Geosat, Gamma Remote Sensing), research institutes (WSL, SLF, UZH, ETHZ) and the Federal Office for the Environment (FOEN).

The Grabengufer rock glacier roots in a steep cirque of highly fractured rock slopes that are part of a large active and deep-seated landslide. The rock glacier is about 450 m long and 100 m wide (Fig. 6.2a). Its tongue terminates at about 2400 m a.s.l. on the steep part that dominates the Grabengufer gully. The latter is a large couloir, which collects most of the material produced by the rapid erosion of the rock glacier front (Fig. 6.2a,c). The Grabengufer gully reaches the Dorfbach torrent (ca. 1900 m a.s.l.), which joins the Mattervispa river 1.5 km downstream in the vicinity of the village of Randa (ca. 1400 m a.s.l.). Repeated observation of the internal structure of the eroding front has not shown significant massive ice but rather debris sealed by interstitial ice (Fig. 6.5b). A basal (probably still frozen) layer with high water content at about 15 m depth was detected using geophysical techniques.

Based on historical knowledge of local people, aerial photographs (provided by Swisstopo) and InSAR data back to 1991 the timing and causes of the current destabilization could be partly reconstructed (Delaloye et al. 2007, 2008, 2010, 2012, Barboux et al. 2012). In 1930, the Grabengufer rock glacier cirque appeared as an accumulation of blocky material without an active front, but rock fall activity from the landslide above was observed. In 1940, a first destabilization of the rock glacier occurred: it can be seen on a vertical air photo from 1941 that active debris flow channels developed from the rock glacier cirque, not only in the Grabengufer gully, but also toward the Gruengarten area, south of the Grabengufer gully. Several dams were built at that time at the rock glacier front and downslope in the forest in order to channel the debris flows back into the Dorfbach torrent (Fig. 6.3). A lateral levée on the left side of the rock glacier indicates the larger width (20–30 m) of the landform during that time compared to today. After this period, no exceptional activity was observed until the 1990s. Several scars bent downstream were clearly visible at the surface of the rock glacier until 2001, which were a result of this earlier crisis.

According to Delaloye et al. (2010) and the analysis of aerial photographs and InSAR data, the current developments started between 1982 and 1988 with progressive overloading of the rooting zone with material from landslide and rock fall activity in the upper areas and building up of a compressive zone. Between 1995 and 2001 this zone propagated to the middle part of the rock glacier, which started to strongly deform (building of new ridges with upstream concavity). The frontal part accelerated up to about 5 m a^{-1} between 2001 and 2005 and later, partly due to its location on steep convex bedrock topography. That way it trailed the entire frozen landform, which completely destabilised in 2009. The surface in the rooting zone was lowered by about 20–30 m.

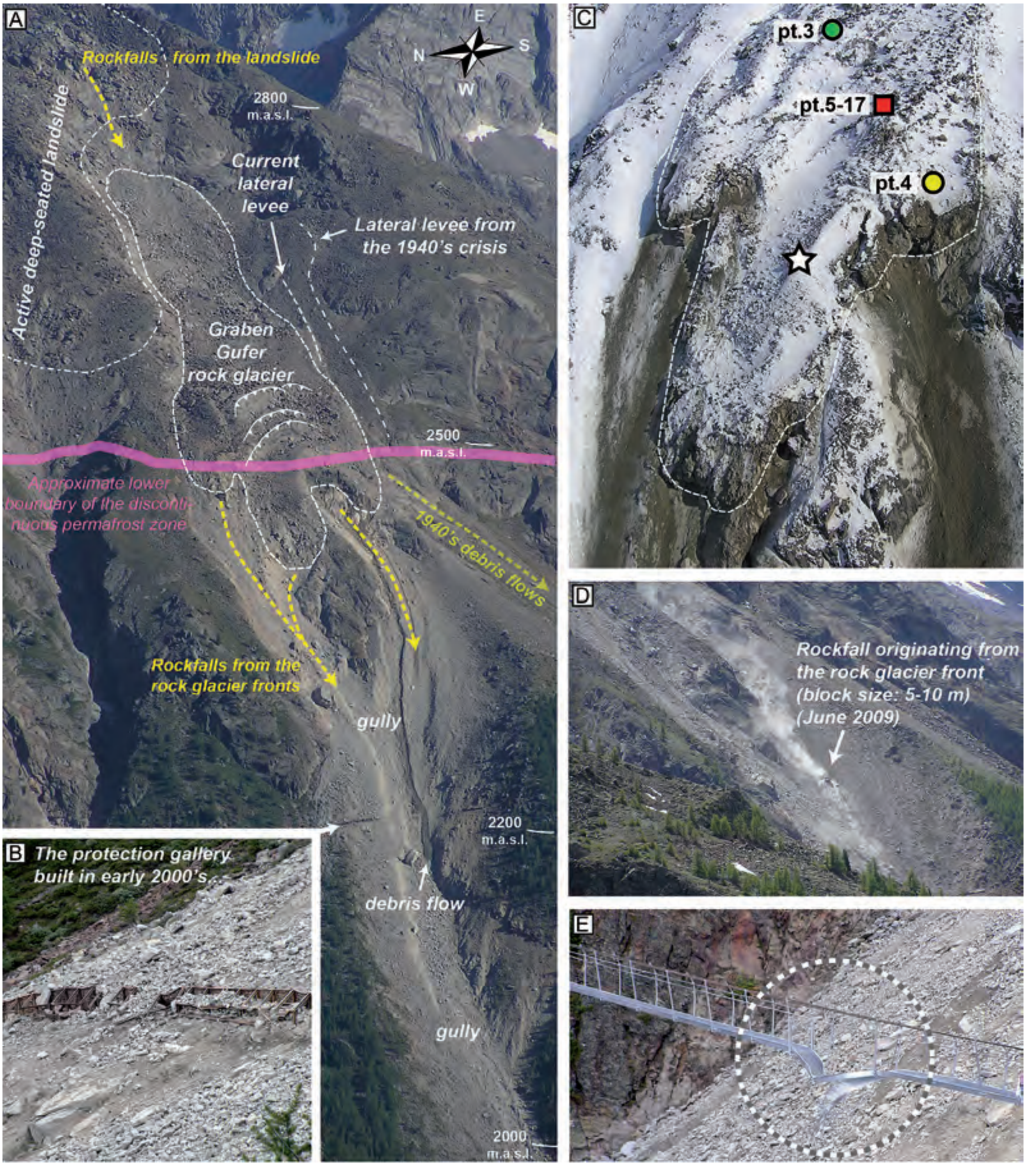


Figure 6.2: *A. Overview of the Grabengufer area (R. Delaloye, 07.08.2009); B. Former protection gallery of the Europaweg (S. Morard, 04.07.2010); C. Frontal erosion of the rock glacier in winter and location of measurement points. The star indicates the most rapid part of the rock glacier (R. Delaloye, 17.03.2010); D. Large rock fall from the rock glacier tongue (R. Delaloye, 12.06.2009); E. Suspension bridge damaged by a rock fall from the upper landslide (R. Delaloye, 23.09.2010).*

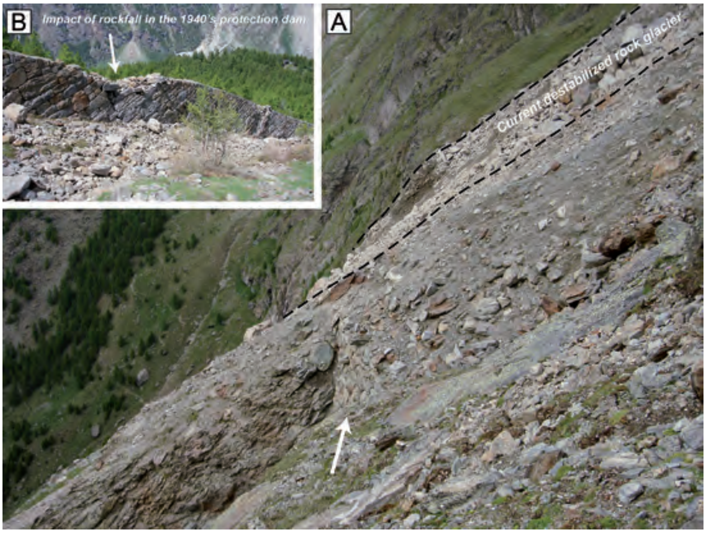


Figure 6.3:
Former protection dams built in the early 1940's on the orographic left side of the Grabengufer rock glacier (D. Abbet, 18.06.2009).
A: Remnants of the upper dam (2470 m a.s.l.), which was destroyed by the rock glacier advance. Only the brighter materials in the background are part of the new destabilisation.
B: Impressive impacts of later (undated) rockfalls on the protection dam in Gruengarten (2100 m a.s.l.).

The maximal activity occurred between July 2009 (start of the in situ monitoring) and February 2010 with surface velocities of about 10–40 cm per day (36–140 m a^{-1}, Figs. 6.4 and 6.6). The fast displacement rates influenced the entire rock glacier, as shown by the large crevasses that opened in the snowpack in winter 2009 (Fig. 6.5a). After the peak activity the flow rates of the Grabengufer rock glacier gradually decreased (Fig. 6.6).

A partial collapse of the rock glacier as it occurred in the southern French Alps in 2006 (Bérard rock glacier, Krysiecki et al. 2008) could not be excluded in 2009, when even in winter rock fall activity was high and debris flow events were triggered from the rock glacier snout (Figs. 6.2a–d). The frontal erosion of the rock glacier was as fast as the displacement leading to a nearly unchanged front position since 2009. The total debris production during this crisis is estimated to be in the order of 100'000 m^3. A direct response to the destabilization of the rock glacier is the changing debris flow activity in the Dorfbach torrent. Significant events (up to more than 10'000 m^3) that can reach the valley bottom are regularly triggered by intense snow melt (e.g., 07.06.2010), rainfall (e.g., 14.08.2010) or the combination of both (e.g., 04.06.2012, Graf et al. 2012). Protection works are being undertaken on the alluvial cone near Randa to prevent damage to existing infrastructure. The Europaweg, a hiking trail, which crosses the Grabengufer gully beneath the rock glacier front, was also affected by the rock glacier crisis. After various protection works and modifications since 2001, a suspension bridge across the Grabengufer gully (2250 m a.s.l.) was built and inaugurated in July 2010. The bridge was badly damaged on 22.09.2010 by a large rock fall (4300 m^3) from the head of the rock glacier rooting zone at about 2860 m a.s.l. (Fig. 6.2e). The source area of this rock fall is part of the upper active deep-seated landslide (surface velocity of 0.1–0.4 m a^{-1}) and underlain by permafrost. The landslide consists of a large mass of rocky material, which was strongly fractured by the movements. The fractures are deeply filled with ice. This unstable area has produced rock falls since decades, but in most cases the deposits only reached the upper and middle zones of the rock glacier. After every larger event, permafrost ice is exposed to the surface and progressive melting triggers further rock falls for months or years, e.g., the rock fall activity in summer 2011 following the large event of September 2010.

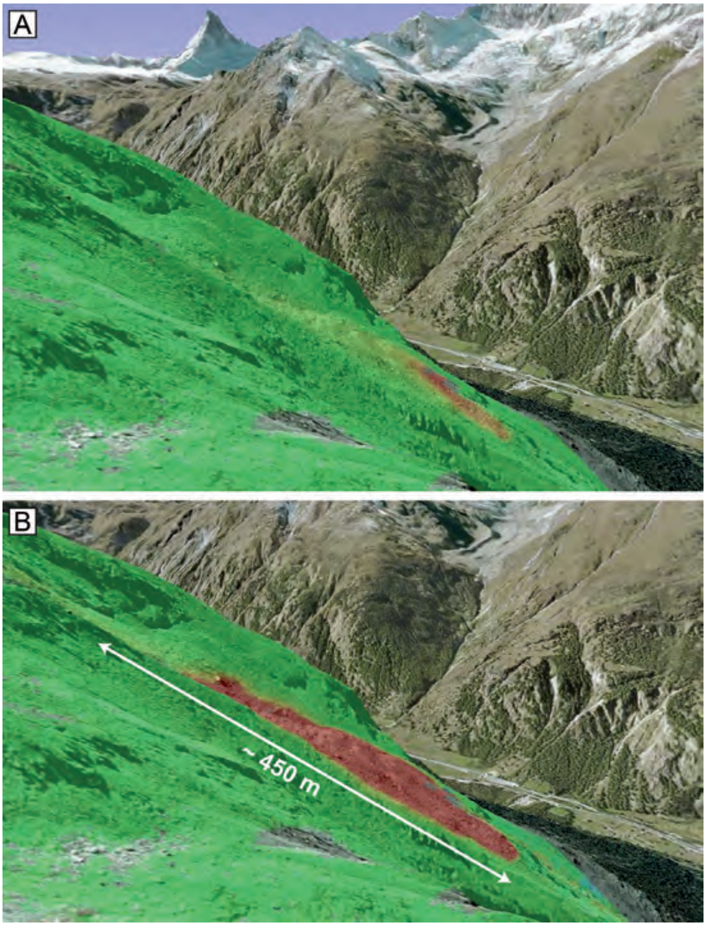


Figure 6.4:
Ground-based radar interferometry survey (Strozzi et al. 2009) of the Grabengufer area on 05.08.2009. Red areas correspond to surface velocities larger than 15 m/year (B. down) and larger than 120 m/year (A. top). DTM Google Earth.

6.3 Summary

The preliminary results from the Furggwanghorn and Grabengufer fast moving rock glaciers, as well as other works carried out on destabilised rock glaciers (e.g., Roer et al. 2008, Delaloye and Morard 2011, Lambiel 2011, Delaloye et al. 2012), obviously show that various factors can lead to the triggering of a destabilization phase and that a common cause for all the cases has not been identified. These factors could be, for instance, related to the (long-term) morphological development of the rock glacier over a convex topography, to the thermal state of the permafrost (climate-induced response) or to an increase of the sediment load. A single or combined influence of these different factors over different time scales is likely to be considered for understanding the initiation of a destabilization phase. Cascading reactions during several decades from the rooting zone to the front of the rock glacier, as occurred in the Grabengufer rock glacier, also have to be taken into consideration.

Figure 6.5:
A. Crevassed remnants of the winter snowpack in the rooting zone of the rock glacier (R. Delaloye, 18.06.2009).
B. Permafrost outcrop at the rock glacier front showing blocky material with cementing ice (R. Delaloye, 01.07.2010).

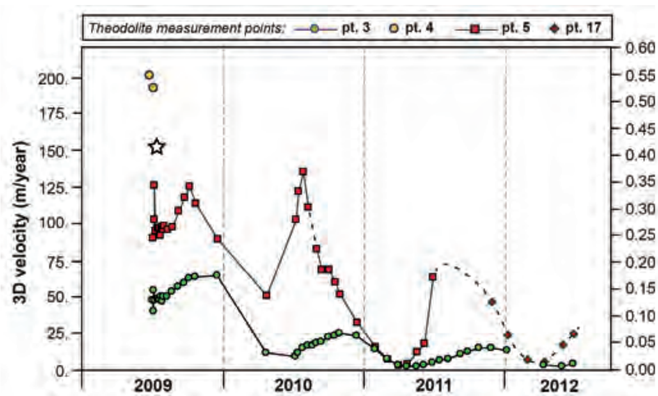


Figure 6.6:
3D surface velocity of the frontal parts of the Grabengufer rock glacier between 2009 and 2012 (left scale: m/year, right scale: m/day). See location of measurement points on Fig. 6.2d. The star corresponds to ground-based radar data (Fig. 6.4 top)

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Photo 4: PERMOS Site Gemmi-Furggentälti in the Bernese Oberland. Photo: Benno Staub.

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Appendix

PERMOS Boreholes

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

Borehole	Region	Morphology	Y CH1903	X CH1903	Elev. m a.s.l.	Slp. (°)	Asp.	Surface mat.
Corvatsch-Murtèl 0200	Engadine	Rock glacier	783175	144692	2672	10	NW	Coarse blocks
Corvatsch-Murtèl 0287	Engadine	Rock glacier	783160	144720	2670	10	NW	Coarse blocks
Dreveneuse 0104	Chablais	Talus slope	557670	124805	1580	30	E	Coarse blocks
Flüela 0102	Engadine	Talus slope	791375	180575	2394	26	NE	Debris
Gemsstock 0106	Urner Alps	Crest	689781	161780	2940	50	NW	Bedrock
Gentianes 0102	Lower Valais	Moraine	589467	103586	2888	20	E	Debris
Lapires 0198	Lower Valais	Talus slope	588070	106080	2500	25	NE	Debris
Lapires 1108	Lower Valais	Talus slope	588099	106092	2500	25	NE	Debris
Lapires 1208	Lower Valais	Talus slope	588028	106027	2535	25	NE	Debris
Les Attelas 0108	Lower Valais	Talus slope	587196	105043	2661	30	W	Debris
Les Attelas 0208	Lower Valais	Talus slope	587243	105040	2689	30	W	Debris
Matterhorn 0205	Upper Valais	Crest	618399	92334	3295	0	–	Bedrock
Muot da Barba Peider 0196	Engadine	Talus slope	791300	152500	2946	38	NW	Debris
Muot da Barba Peider 0296	Engadine	Talus slope	791300	152500	2941	38	NW	Debris
Muragl 0199	Engadine	Rock glacier	791025	153726	2536	15	W	Coarse blocks
Muragl 0499	Engadine	Rock glacier	791017	153688	2549	15	SW	Coarse blocks
Ritigraben 0105	Upper Valais	Rock glacier	631755	113775	2690	0	–	Coarse blocks
Schafberg 0190	Engadine	Rock glacier	790944	152590	2754	0	–	Coarse blocks
Schafberg 0290	Engadine	Rock glacier	790855	152745	2732	0	–	Coarse blocks
Schilthorn 5198	Bernese Oberland	Crest	630365	156410	2909	30	NE	Debris
Schilthorn 5000	Bernese Oberland	Crest	630350	156410	2910	30	NE	Debris
Schilthorn 5200	Bernese Oberland	Crest	630350	156410	2910	30	NE	Debris
Stockhorn 6000	Upper Valais	Crest	629878	92876	3410	8	S	Debris
Stockhorn 6100	Upper Valais	Crest	629867	92850	3410	8	S	Debris
Tsaté 0104	Lower Valais	Crest	608490	106400	3040	30	W	Bedrock

Table A.1b: Instrumentation of the boreholes.

Borehole	Since	Depth (m)	Lowest S. (m)	#Therm.	Sensors	Access	Calib.	Institution
Corvatsch-Murtèl 0200	2000	63.20	62.00	30	YSI 44006	remote	2000	ETHZ
Corvatsch-Murtèl 0287	1987	62.00	57.95	46	YSI 44006	remote	1997	UZH
Dreveneuse 0104	2004	15.00	14.50	12	MAAD	on site	2006	UNIFR
Flüela 0102	2002	23.00	20.00	12	YSI 46006	on site	2002	SLF
Gemsstock 0106	2006	40.00	39.50	27	YSI 44008	on site	2005	SLF
Gentianes 0102	2002	20.04	20.04	11	MAAD	on site	2002	UNIL
Lapires 0198	1998	19.60	19.60	12	YSI 44031	remote	1998	UNIFR
Lapires 1108	2008	40.00	39.00	28	YSI 44031	remote	2008	UNIFR
Lapires 1208	2008	35.00	34.00	18	YSI 44031	remote	2008	UNIFR
Les Attelas 0108	2008	26.00	24.00	12	MAAD	on site	2008	UNIL
Les Attelas 0208	2008	21.00	20.00	11	MAAD	on site	2008	UNIL
Matterhorn 0205	2005	53.00	52.90	12	YSI 44008	on site	2005	SLF
Muot da Barba Peider 0196	1996	18.00	17.50	10	YSI 44008	on site	1996	SLF
Muot da Barba Peider 0296	1996	18.00	17.50	10	YSI 44008	on site	1996	SLF
Muragl 0199	1999	70.20	69.70	18	YSI 44006	on site	1999	ETHZ
Muragl 0499	1999	71.00	69.59	22	YSI 44006	on site	1999	ETHZ
Ritigraben 0105	2002	30.00	14.00	30	YSI 44006	remote	2002	SLF
Schafberg 0190	1990	67.00	15.90	15	YSI 46006	on site	2005	SLF
Schafberg 0290	1990	37.00	25.20	10	YSI 46006	on site	1997	SLF
Schilthorn 5198	1998	14.00	13.00	14	YSI 44006	remote	1998	UZH
Schilthorn 5000	2000	101.00	100.00	30	YSI 44006	remote	1999	UZH
Schilthorn 5200	2000	100.00	87.00	19	YSI 44006	remote	1999	UZH
Stockhorn 6000	2000	100.00	98.30	30	YSI 44006	remote	2000	UNIFR
Stockhorn 6100	2000	31.00	17.00	18	YSI 44006	remote	2000	UNIFR
Tsaté 0104	2004	20.00	19.50	11	MAAD	on site	2006	UNIL

Active Layer Depths

Table A.2a: Depth and date of maximum active layer thickness of for the Borehole COR_0287 1988–1996.

Year	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
ALT	3.35	3.22	3.12	3.27	3.37	3.40	3.45	3.48	3.44	3.38
Date	24.09	03.08	01.10	01.09	23.09	28.08	23.08	12.09	16.08	29.08

Table A.2b: Depth and date of maximum active layer thickness of PERMOS boreholes 1997–1999.

Name	1997		1998		1999	
	ALT	Date	ALT	Date	ALT	Date
COR_0287	3.44	15.09	3.47	21.08	3.43	31.08
LAP_0198					3.65	07.10
MBP_0196	0.66	10.09	0.87	22.08	0.88	19.09
MBP_0296	1.69	16.09	1.91	24.08	1.93	19.09
SBE_0290	3.17	18.08	3.18	14.08	3.17	28.08
SCH_5198			4.30	01.11	4.43	10.10

Table A.2c: Depth and date of maximum active layer thickness of PERMOS boreholes 2000–2006.

Name	2000		2001		2002		2003		2004		2005		2006	
	ALT	Date	ALT	Date	ALT	Date	ALT	Date	ALT	Date	ALT	Date	ALT	Date
COR_0200	–	–	–	–	3.35	03.09	3.25	31.08	2.89	13.09	2.49	05.09	2.48	14.09
COR_0287	3.45	30.08	3.48	05.09	3.44	05.09	3.51	24.08	3.51	07.09	3.5	08.09	3.501	13.09
DRE_0104	–	–	–	–	–	–	–	–	–	–	–	–	–	–
FLU_0102	–	–	–	–	–	–	2.96	26.08	2.9	13.09	2.93	18.09	2.95	25.09
GEN_0102	–	–	–	–	–	–	1.42	30.08	1.42	14.09	1.48	05.09	1.38	05.10
LAP_0198	3.75	15.10	3.85	01.10	–	–	4.2	08.10	4.55	01.10	4.65	11.10	–	–
MAT_0205	–	–	–	–	–	–	–	–	–	–	–	–	3.19	06.08
MBP_0196	0.74	18.09	0.84	30.08	0.78	09.09	1.63	01.09	1.01	17.09	0.95	12.09	1.06	06.10
MBP_0296	1.9	01.09	1.92	31.08	1.86	09.09	2.35	17.09	2.24	21.09	1.96	14.09	1.98	29.09
MUR_0499	–	–	3.47	03.09	3.29	08.09	3.46	04.09	4.17	05.10	4.43	22.09	4.49	06.09
RIT_0105	–	–	–	–	–	–	–	–	–	–	4.39	02.10	4.31	23.09
SBE_0190	–	–	–	–	–	–	–	–	–	–	3.9	08.09	3.91	16.09
SBE_0290	4.98	04.09	5.04	12.09	4.87	08.09	5.1	30.08	5.04	18.09	4.97	14.09	4.88	05.10
SCH_5000	–	–	–	–	3.04	23.10	8.27	06.11	4.78	28.09	3.67	09.10	3.74	07.10
SCH_5198	4.88	06.10	–	–	4.6	01.10	8.96	28.10	4.81	06.10	4.8	06.10	4.84	20.10
SCH_5200	–	–	–	–	–	–	2.98	31.10	3.33	08.10	2.27	18.09	1.28	26.09
STO_6000	–	–	–	–	2.88	20.09	4.28	20.10	3.71	20.09	–	–	3.09	20.09
STO_6100	–	–	–	–	3.39	20.09	4.07	20.10	3.92	20.10	–	–	3.47	20.09
TSA_0104	–	–	–	–	–	–	–	–	–	–	6.47	22.10	–	–

Table A.2d: Depth and date of maximum active layer thickness of PERMOS boreholes 2007–2010.

Name	2007		2008		2009		2010	
	ALT	Date	ALT	Date	ALT	Date	ALT	Date
ATT_0108	–	–	–	–	3.93	06.09	3.83	28.08
ATT_0208	–	–	–	–	5.75	30.08	4.95	26.08
COR_0200	2.47	16.08	2.48	06.09	2.48	03.09	2.43	24.08
COR_0287	3.51	22.08	3.51	04.09	3.54	08.09	3.54	26.08
DRE_0104	–	–	–	–	–	–	–	–
FLU_0102	2.98	01.09	2.98	14.09	2.95	01.09	2.94	29.08
GEN_0102	1.47	26.09	–	–	2.14	02.10	2.01	25.09
LAP_0198	4.65	01.10	4.75	01.10	5.26	19.10	5.21	04.10
LAP_1108	–	–	–	–	4.80	08.10	4.44	13.10
LAP_1208	–	–	–	–	–	–	4.08	27.08
MAT_0205	3.32	08.09	2.89	17.09	3.66	01.10	2.98	03.09
MBP_0196	1.00	01.09	1.00	15.09	0.99	28.09	–	–
MBP_0296	1.97	05.09	2.05	22.09	2.02	04.10	2.03	04.09
MUR_0499	4.48	16.09	–	–	4.48	20.08	4.48	05.09
RIT_0105	4.05	04.09	4.27	07.09	4.20	08.10	3.92	31.08
SBE_0190	3.96	20.08	3.97	07.09	4.12	04.11	–	–
SBE_0290	5.03	24.08	5.03	16.09	5.11	05.09	5.10	03.09
SCH_5000	3.14	04.10	3.89	13.09	7.18	21.11	–	–
SCH_5198	4.66	09.10	4.97	25.09	6.99	23.10	6.80	20.09
SCH_5200	1.16	09.10	1.89	17.09	2.96	01.11	–	–
STO_6000	–	–	3.27	20.09	–	–	3.30	20.09
STO_6100	–	–	3.42	20.09	4.44	20.11	4.45	20.12
TSA_0104	6.47	30.10	6.44	03.10	6.97	26.10	6.80	06.10

Attelas 0108

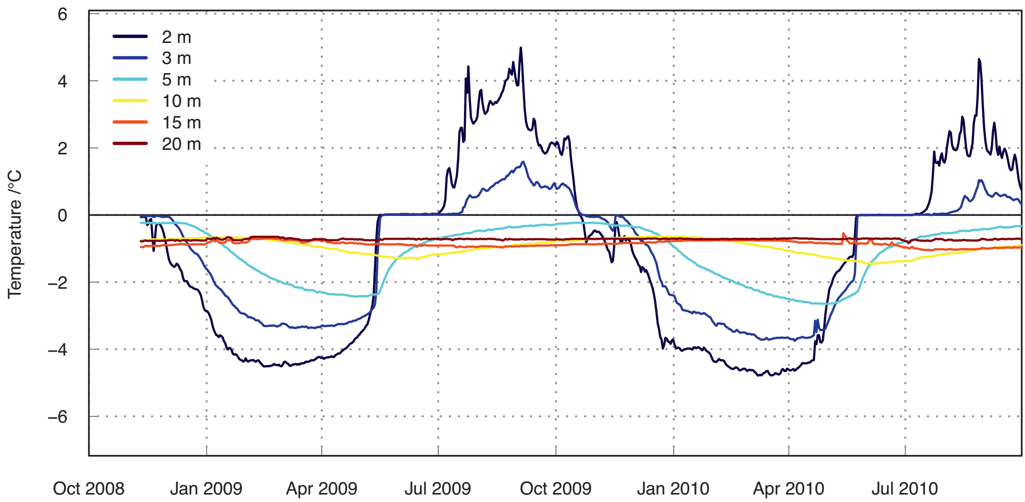


Figure A.1: Temperature-time plot of the borehole Attelas 0108.

Attelas 0208

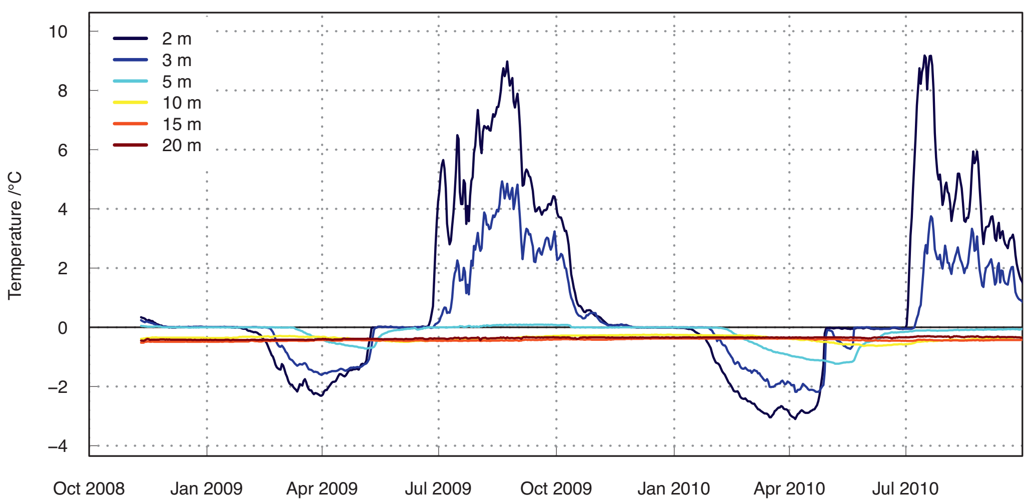


Figure A.2: Temperature-time plot of the borehole Attelas 0208.

Corvatsch-Murtèl 0287

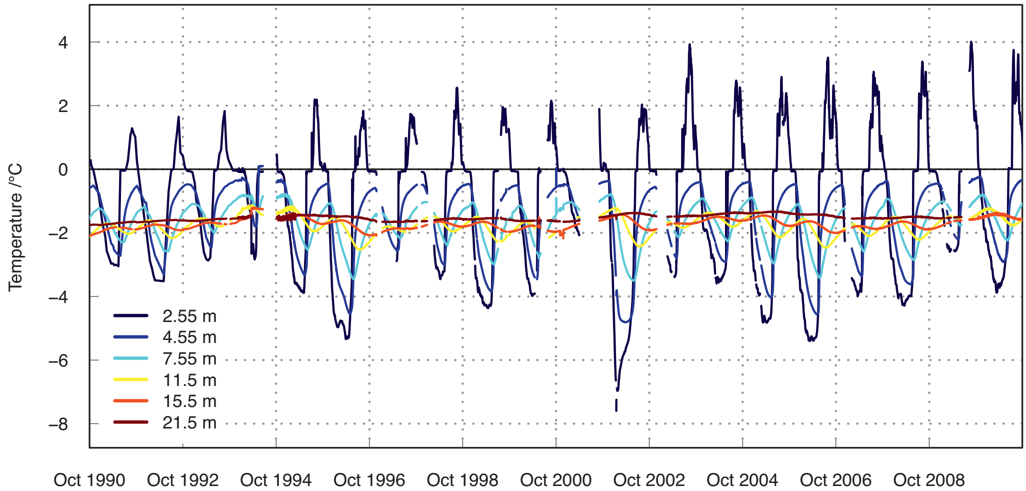


Figure A.3: Temperature-time plot of the borehole Murtèl-Corvatsch 0287.

Corvatsch-Murtèl 0200

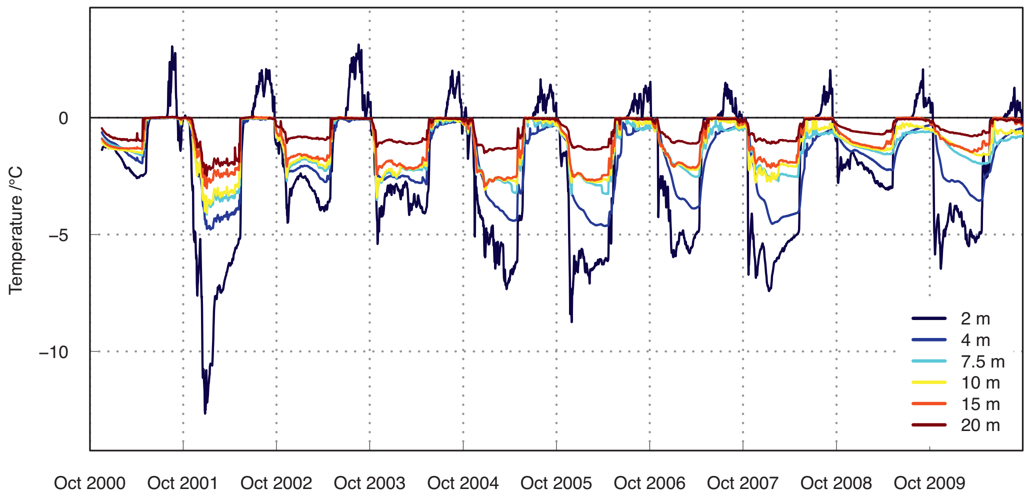


Figure A.4: Temperature-time plot of the borehole Murtèl-Corvatsch 0200.

Dreveneuse 0104

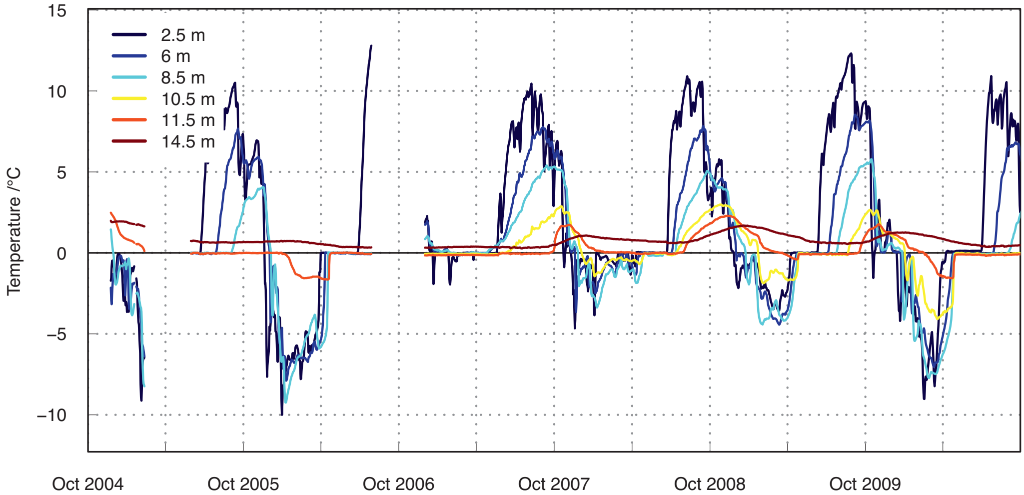


Figure A.5: *Temperature-time plot of the borehole Dreveneuse 0104.*

Flüela 0102

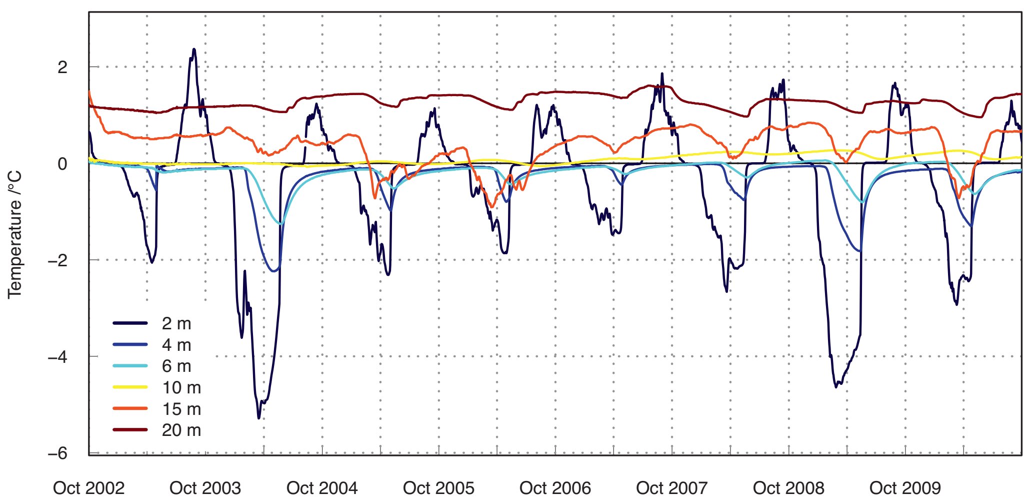


Figure A.6: *Temperature-time plot of the borehole Flüela 0102.*

Gemsstock 0106

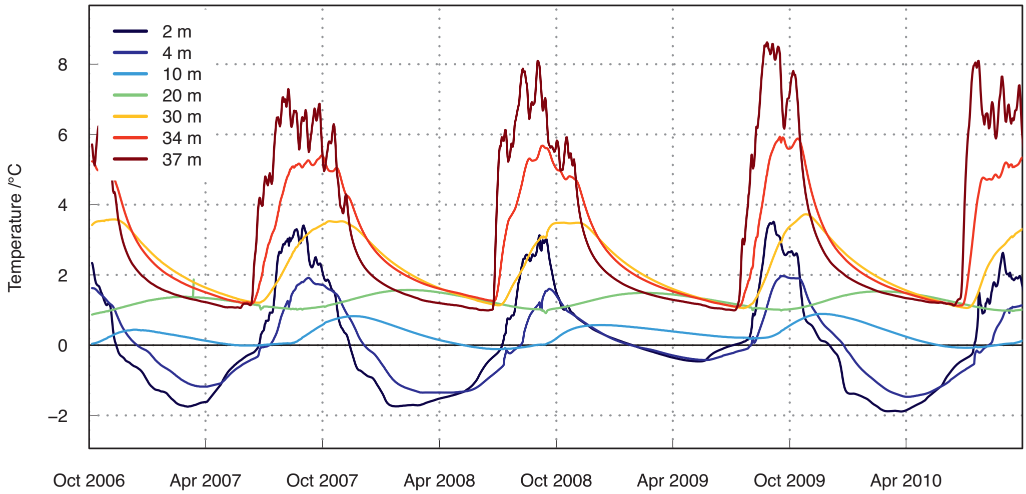


Figure A.7: Temperature-time plot of the borehole Gemsstock 0106

Gentianes 0102

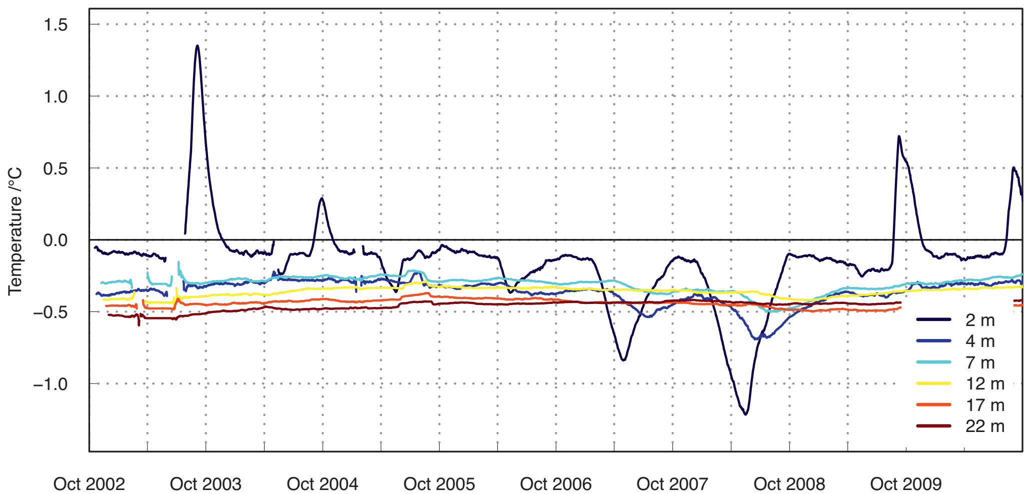


Figure A.8: Temperature-time plot of the borehole Gentianes 0102.

Lapires 0198

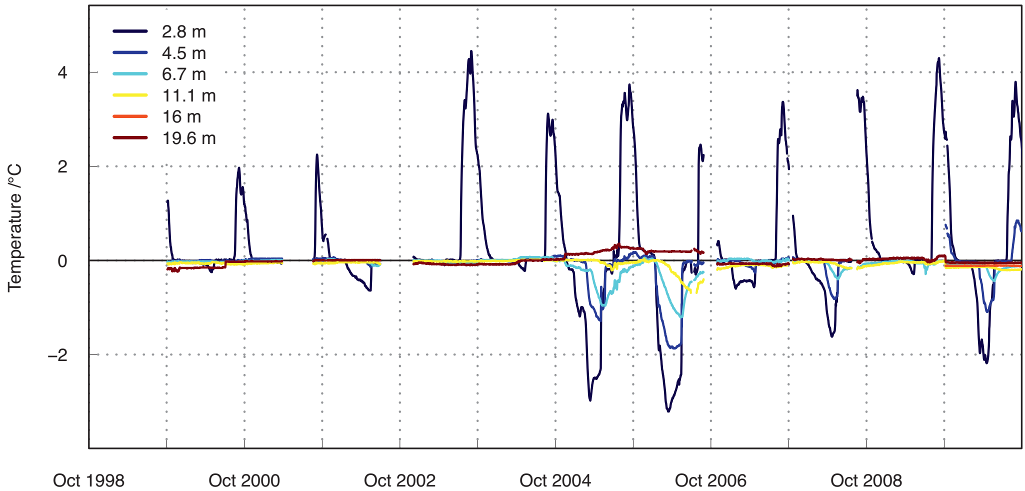


Figure A.9: *Temperature-time plot of the borehole Lapires 0198.*

Lapires 1108

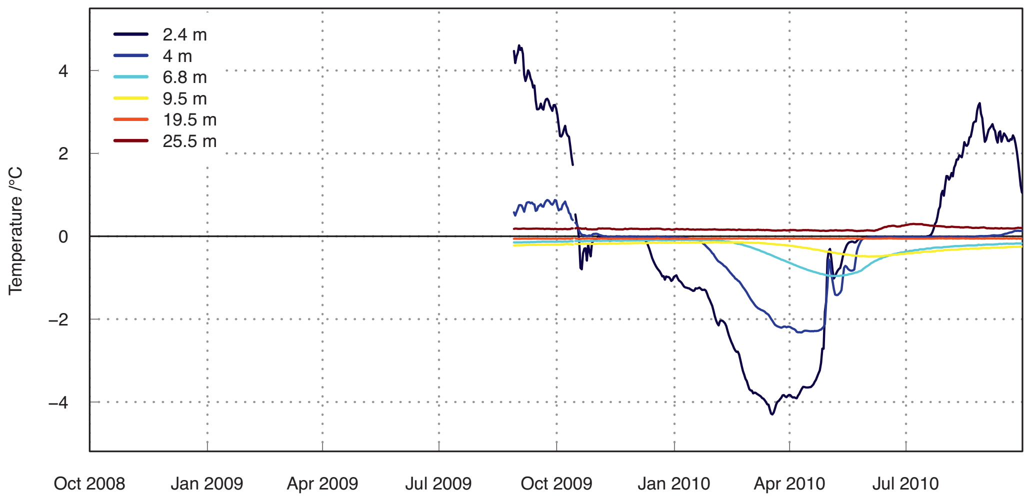


Figure A.10: *Temperature-time plot of the borehole Lapires 1108.*

Lapires 1208

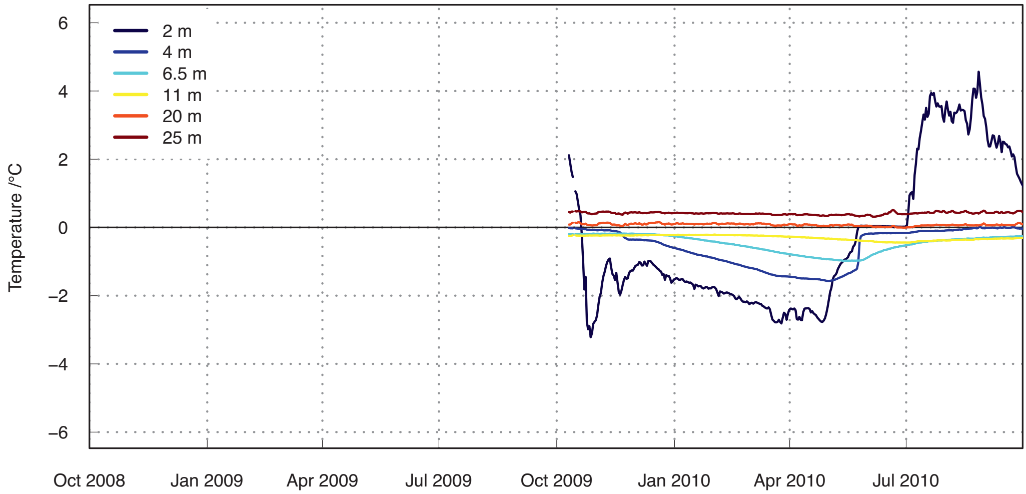


Figure A.11: *Temperature-time plot of the borehole Lapires 1208.*

Matterhorn 0205

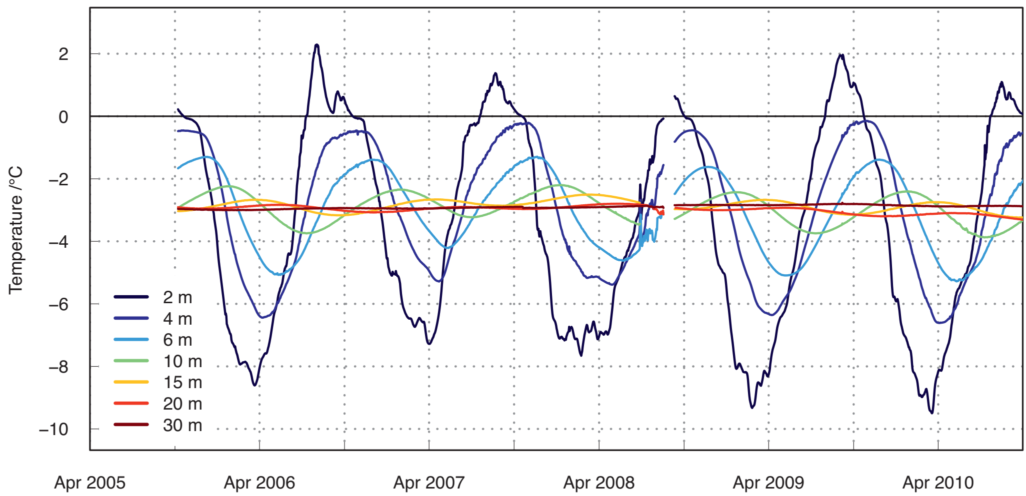


Figure A.12: *Temperature-time plot of the borehole Matterhorn 0205.*

Muot Da Barba Peider 0196

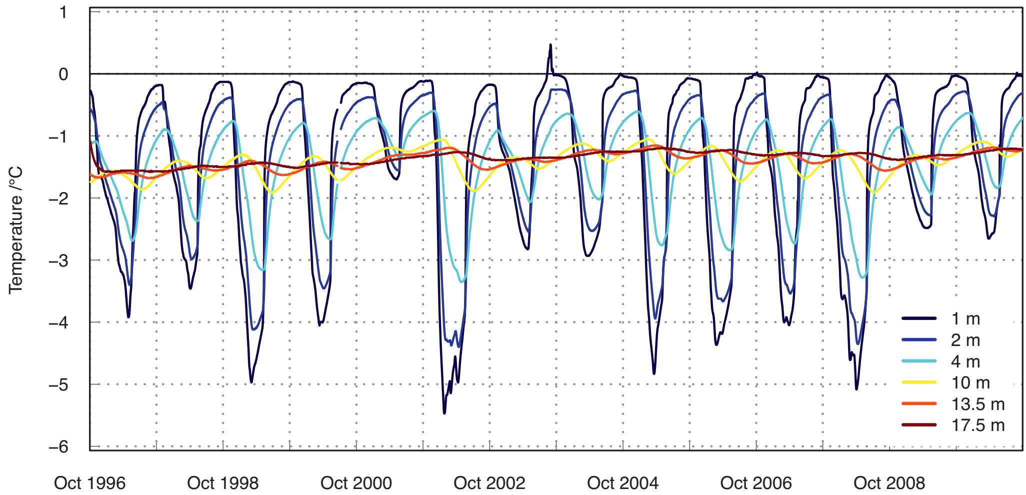


Figure A.13: Temperature-time plot of the borehole Muot Da Barba Peider 0196.

Muot Da Barba Peider 0296

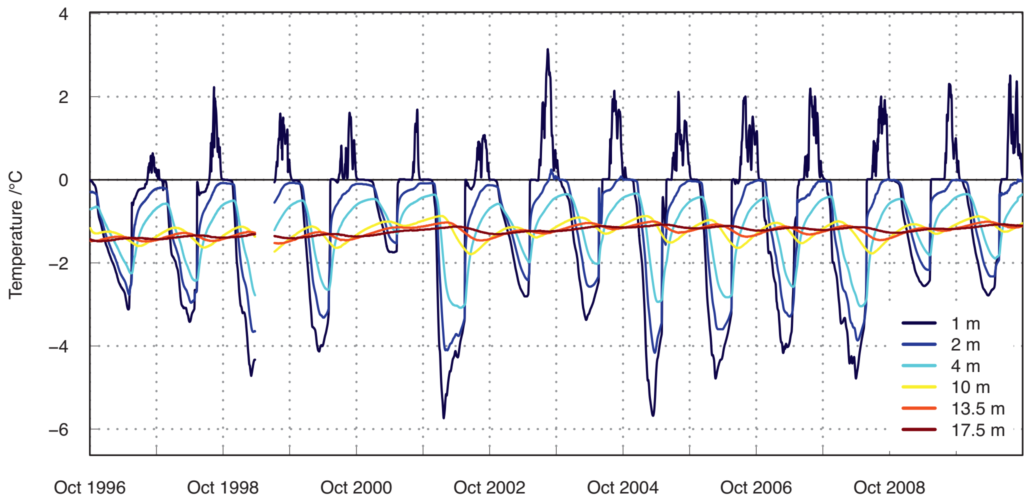


Figure A.14: Temperature-time plot of the borehole Muot Da Barba Peider 0296.

Muragl 0199

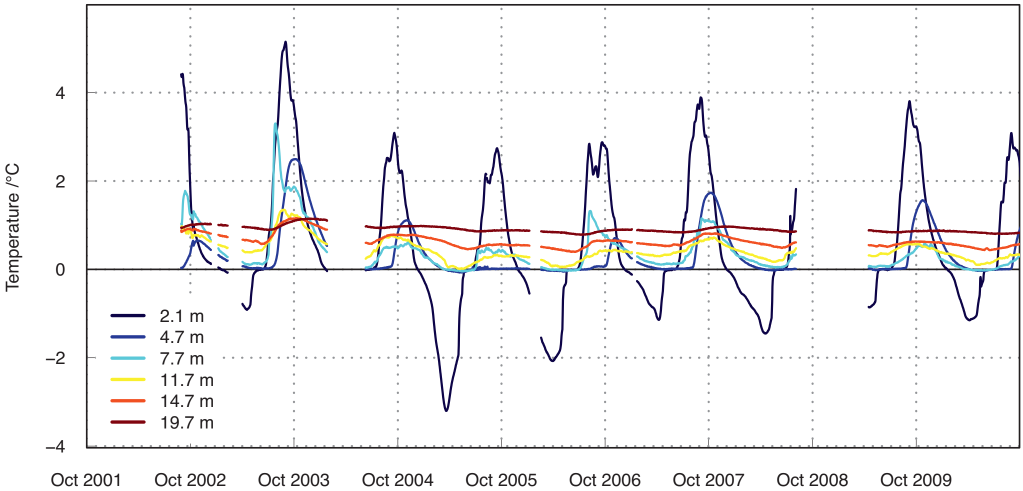


Figure A.15: Temperature-time plot of the borehole Muragl 0199.

Muragl 0499

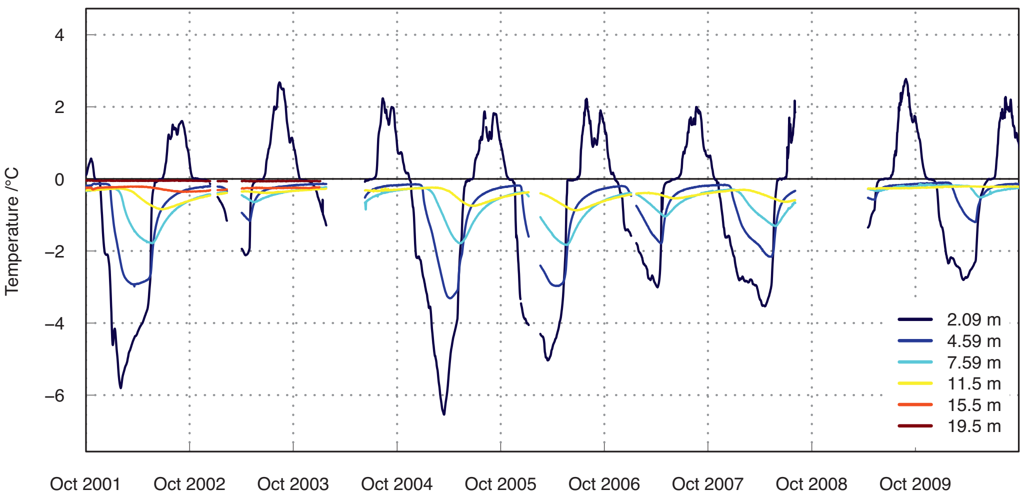


Figure A.16: Temperature-time plot of the borehole Muragl 0499.

Ritigraben 0105

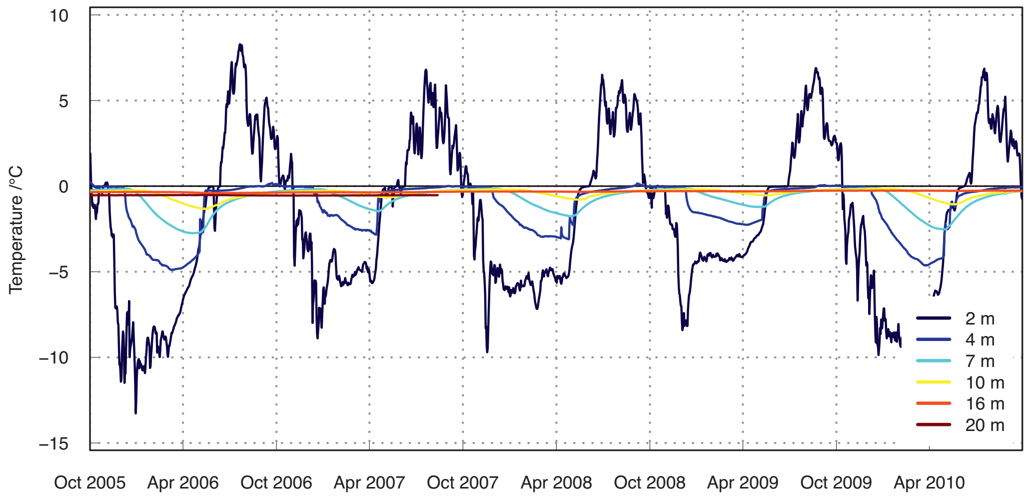


Figure A.17: Temperature-time plot of the borehole Ritigraben 0105.

Schafberg 0190

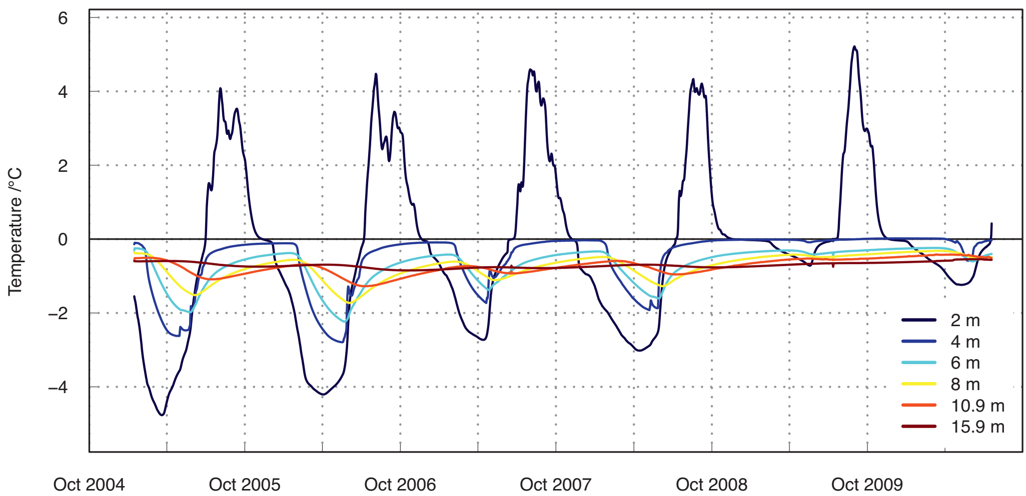


Figure A.18: Temperature-time plot of the borehole Schafberg 0190.

Schafberg 0290

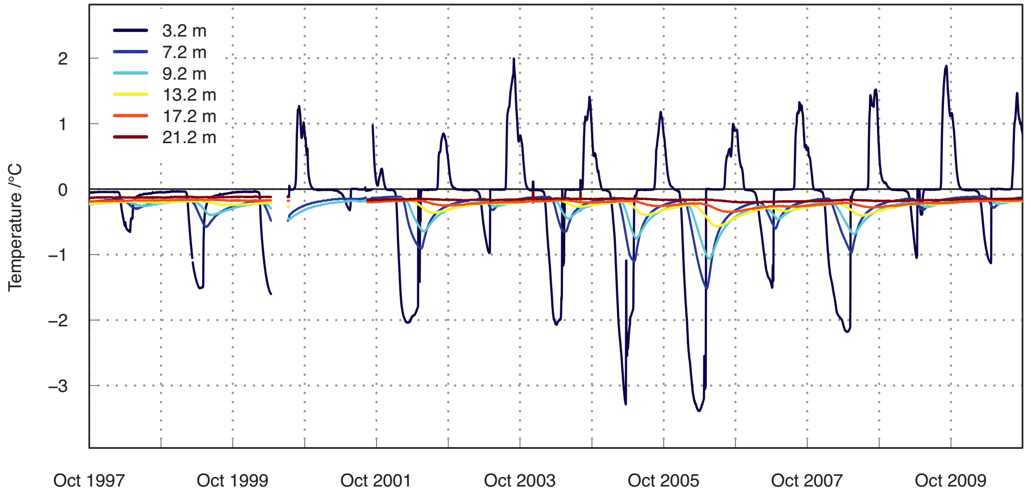


Figure A.19: *Temperature-time plot of the borehole Schafberg 0290.*

Schilthorn 5198

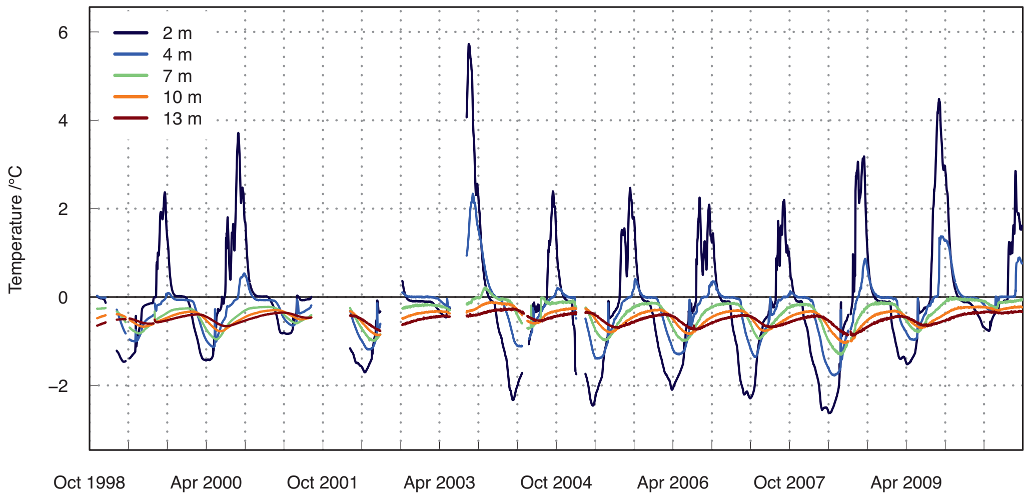


Figure A.20: *Temperature-time plot of the borehole Schilthorn 5198.*

Schilthorn 5000

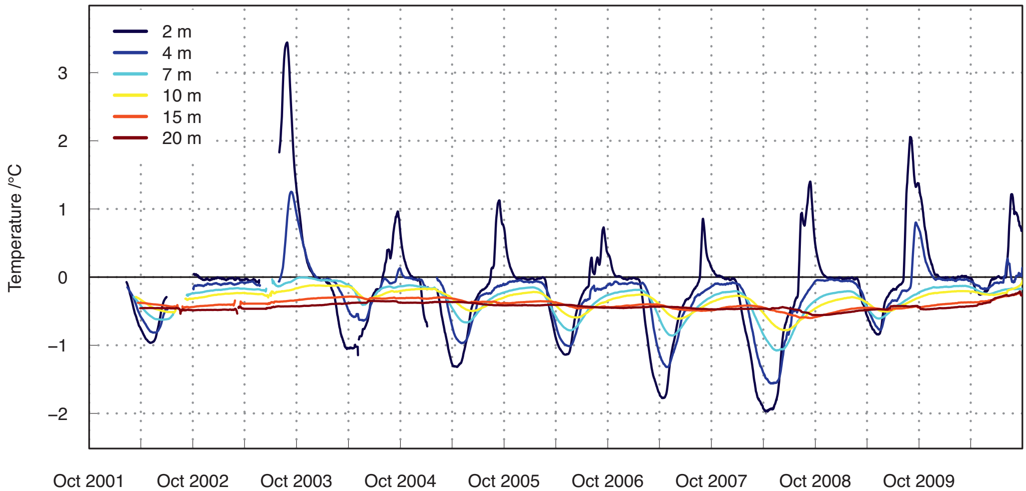


Figure A.21: *Temperature-time plot of the borehole Schilthorn 5000.*

Schilthorn 5200

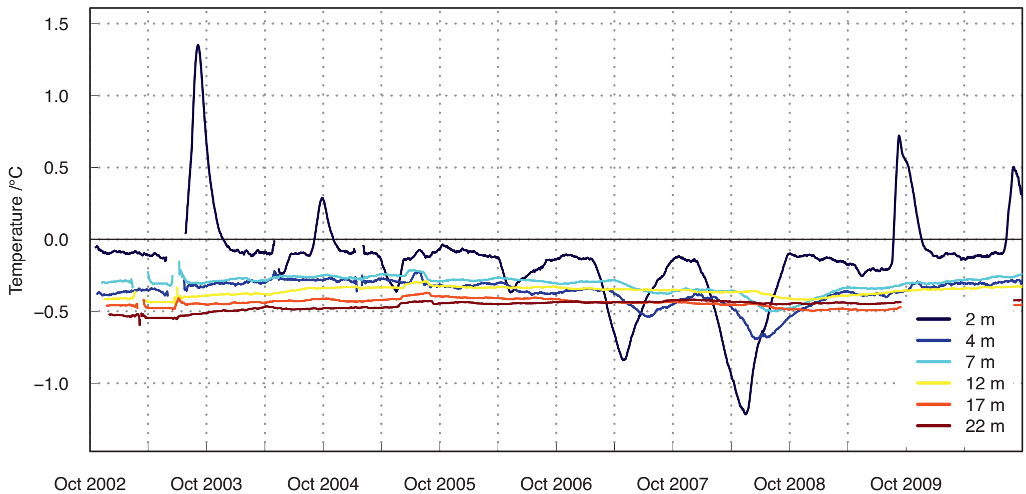


Figure A.22: *Temperature-time plot of the borehole Schilthorn 5200.*

Stockhorn 6000

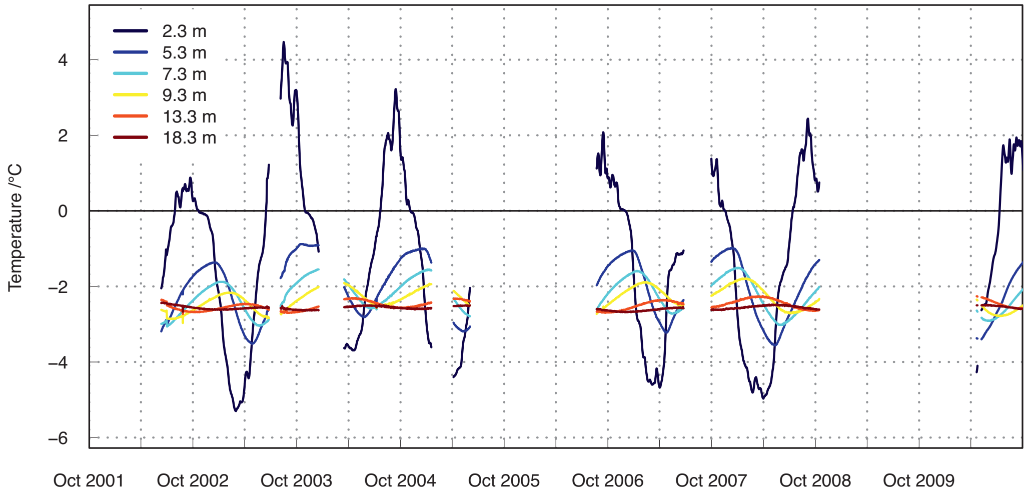


Figure A.23: Temperature-time plot of the borehole Stockhorn 6000.

Stockhorn 6100

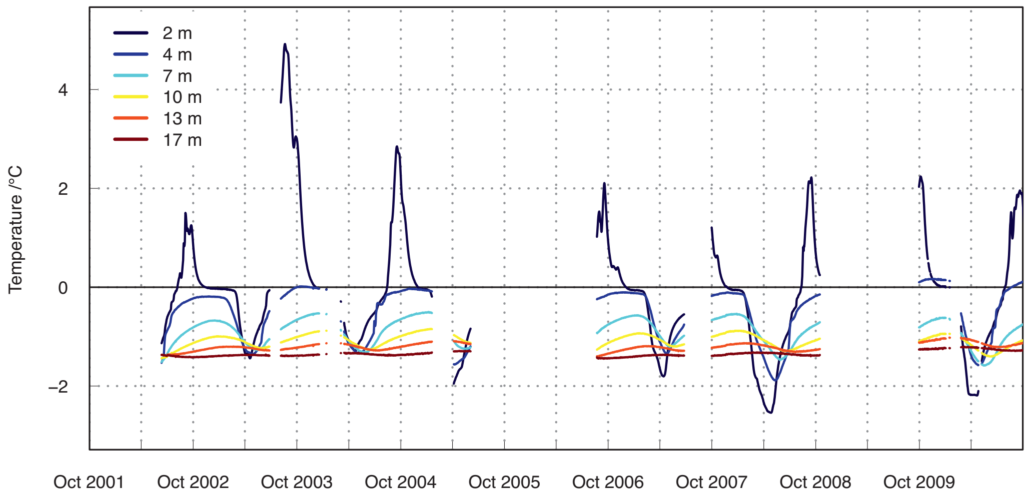


Figure A.24: Temperature-time plot of the borehole Stockhorn 6100.

Tsaté 0104

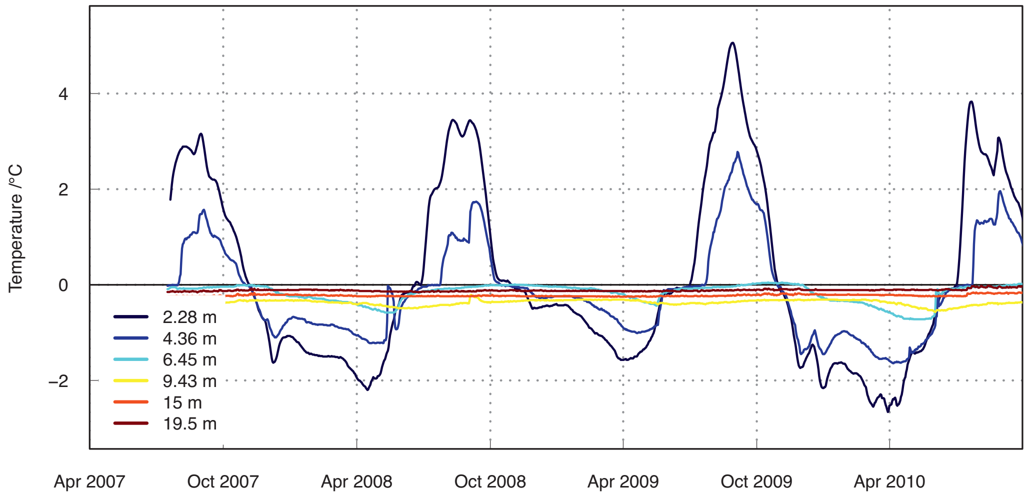


Figure A.25: Temperature-time plot of the borehole Tsaté 0104.

PERMOS Rock Temperature Sites

Table A.3a: Locations of rock temperature loggers.

Name	Region	Responsible	Coordinates	Elevation (m a.s.l.)	Slope (°)	Aspect (°)	Skyview
Birg East 2	Bernese Oberland	UZH	632285/156996	2620	0	0	0.99
Birg vertical	Bernese Oberland	UZH	631995/156799	2670	85	205	0.48
Birg West 2	Bernese Oberland	UZH	630834/156689	2680	22	130	0.92
Eigerfenster	Bernese Oberland	UZH	643307/159034	2860	90	325	0.48
Eismeer	Bernese Oberland	UZH	643830/158049	3150	87	100	0.51
Engital	Bernese Oberland	UZH	632167/157427	2410	10	130	0.88
Jungfrau East Ridge N	Bernese Oberland	UZH	640816/155013	3750	70	145	0.57
Jungfrau East Ridge S	Bernese Oberland	UZH	640816/155025	3750	55	344	0.77
Moench West Ridge	Bernese Oberland	UZH	642189/155603	3550	72	288	0.65
Schilthornhuette	Bernese Oberland	UZH	632622/157941	2450	0	0	0.93
Schwarzgrat	Bernese Oberland	UZH	630492/156597	2800	0	0	0.96
Corvatsch Hubbel	Engadine	UZH	783822/145760	2545	0	0	0.96
Corvatsch Middle Flat	Engadine	UZH	783182/145226	2690	8	320	0.99
Corvatsch Middle Ridge	Engadine	UZH	783370/144916	2784	85	278	0.49
Corvatsch Snow Canon	Engadine	UZH	783463/145390	2649	0	0	0.99
Corvatsch Top Flat	Engadine	UZH	783100/143413	3300	0	0	0.92
Corvatsch Top Gate	Engadine	UZH	783150/143538	3285	72	333	0.65
Corvatsch Top Ridge	Engadine	UZH	783103/143427	3300	58	181	0.73
Fuorcla	Engadine	UZH	784587/144561	2740	11	344	0.97
Fuorcla North	Engadine	UZH	784615/145365	2765	23	11	0.9
Mandra East	Engadine	UZH	784665/145584	2805	90	88	0.47
Mandra South	Engadine	UZH	784607/145527	2830	98	185	0.39
Murtèl Front	Engadine	UZH	783028/144838	2630	15	20	0.93
BB-h01	Lower Valais	UniFR	605150/113933	2600	0	0	0.99
BB-v01	Lower Valais	UniFR	606217/112954	3100	90	75	0.46
BB-v02	Lower Valais	UniFR	606193/112951	3120	75	308	0.57
BB-v03	Lower Valais	UniFR	606137/112930	3140	95	198	0.45
BB-v04	Lower Valais	UniFR	605052/113919	2590	85	278	0.48
BB-v05	Lower Valais	UniFR	605091/113946	2590	90	50	0.41
La-h01	Lower Valais	UniFR	587650/105875	2735	0	0	0.99
La-v01	Lower Valais	UniFR	588670/106300	2380	95	325	0.38
La-v02	Lower Valais	UniFR	587740/106089	2730	95	39	0.39
La-v03	Lower Valais	UniFR	587767/106142	2720	90	140	0.43
La-v04	Lower Valais	UniFR	587558/105773	2700	80	225	0.55
La-v05	Lower Valais	UniFR	587693/105622	2770	10	341	0.36

Mean Annual Rock Temperatures

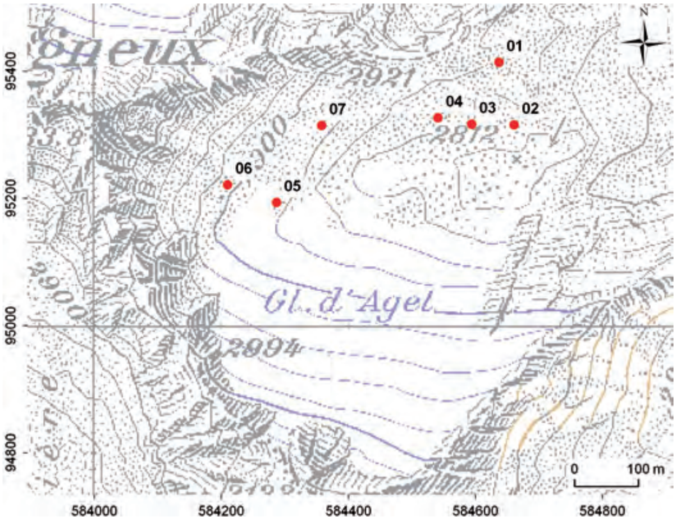
Table A.3b: *Mean annual rock temperatures MART (for hydrological years). Only time series with minimum 350 days of measurement per year are considered for calculating annual means.*

Name	03/04	04/05	05/06	06/07	07/08	08/09	09/10
Birg East 2	0.59	0.34	–	–	1.47	1.45	1.27
Birg vertical	5.47	5.61	–	–	–	6.01	4.82
Birg West 2	3.04	3.17	2.86	3.38	2.36	–	–
Eigerfenster	–0.56	–0.93	–0.95	0.48	–0.48	–	–0.77
Eismeer	–	1.08	1.02	1.30	–1.60	–	–
Engital	–	–0.10	1.20	2.45	–	2.96	2.08
Jungfrau East Ridge N	–	–	–7.72	–6.15	–7.13	–	–7.41
Jungfrau East Ridge S	–	–	0.72	1.64	0.78	–	0.42
Moench West Ridge	–	–4.84	–5.12	–3.42	–4.26	–	–
Schilthornhuette	–	2.42	2.58	–	–	–	–
Schwarzgrat	–	0.04	–	–	–	0.35	–
Corvatsch Hubbel	3.63	–	–	4.11	–	–	3.74
Corvatsch Middle Flat	1.92	0.96	1.35	3.19	1.23	3.20	2.63
Corvatsch Middle Ridge	–	0.45	0.54	2.08	1.32	1.49	1.09
Corvatsch Snow Canon	–	0.47	1.25	3.03	1.04	3.31	2.51
Corvatsch Top Flat	–	–	–	-0.30	–2.48	–	–2.22
Corvatsch Top Gate	–	–3.72	–3.67	–2.16	–3.00	–	–3.25
Corvatsch Top Ridge	–	–	–	–	–	–	1.05
Fuorcla	–	1.13	1.54	2.32	1.29	2.16	2.25
Fuorcla North	–	0.91	1.43	3.34	0.82	3.31	2.81
Mandra East	–	2.66	2.83	4.08	–	–	2.83
Mandra South	–	5.65	5.98	6.98	–	–	5.72
Murtèl Front	2.52	2.32	2.10	2.44	1.70	–	–
BB-h01	–	1.76	0.95	2.12	–	–	–
BB-v01	–	1.05	1.01	2.28	1.46	–	–
BB-v02	–	–1.36	–1.28	–0.04	–0.70	–	–
BB-v03	–	1.40	1.29	2.53	1.87	–	–
BB-v04	–	3.24	3.13	4.44	3.55	–	–
BB-v05	–	0.74	0.83	2.05	1.18	–	–
La-h01	–	0.94	0.32	1.14	1.06	–	–
La-v01	–	2.61	2.73	3.92	3.11	–	2.83
La-v02	–	2.56	3.02	3.97	3.41	–	2.89
La-v03	–	5.33	4.98	5.91	5.33	–	–
La-v04	–	4.44	4.44	5.75	5.12	–	3.82
La-v05	–	–	0.39	1.72	0.87	–	0.34

GST Aget

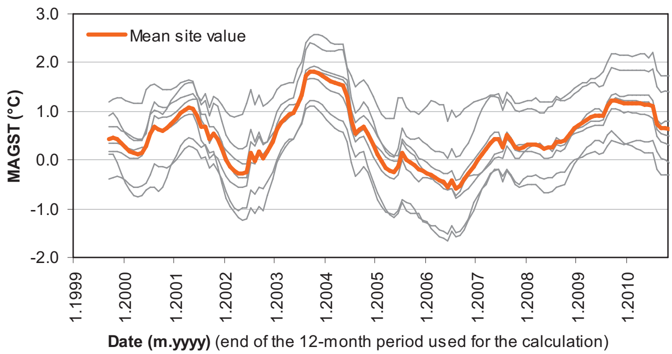
Region: Bagnes Valley (Lower Valais)

Landform(s): Glacier forefield, back creeping push-moraine, talus slope



GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
01	2856	1.22	0.55
02	2827	1.89	1.39
03	2835	0.40	0.05
04	2849	1.04	0.37
05	2880	1.32	0.75
06	2908	2.17	1.74
07	2882	0.60	–0.30



Mean values since start of series

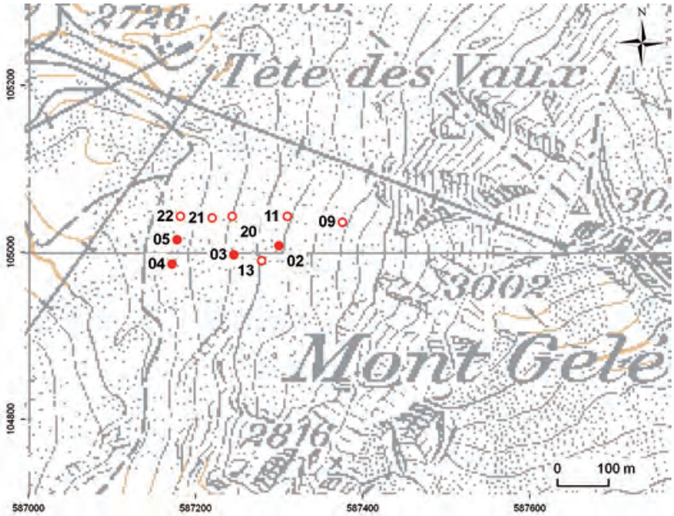
MAGST:	+0.50°C
Snow free date:	03. Jul
Ground Freezing Index	–272 °C.d
Ground Thawing Index	+460 °C.d

Trend (until 2009/10) of mean values

	since 1998/99	since 1999/00	since 2001/02
MAGST (°C/year)	+0.02	+0.02	+0.02
Snow free date (day/year)	-1.0	+0.1	+0.4
Ground Freezing Index (°C/year)	-9.9	-6.1	+0.6
Ground Thawing Index (°C/year)	+10.4	+5.4	+3.1

GST Les Attelas

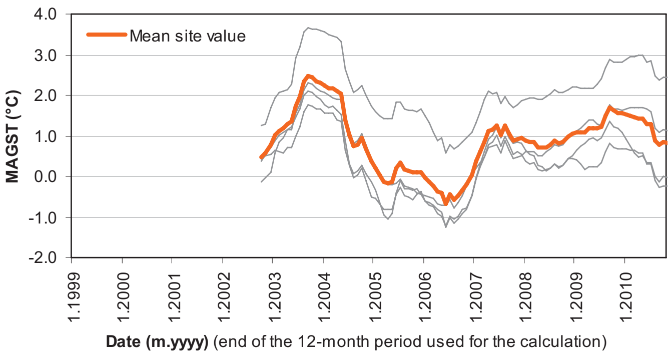
Region: Bagnes Valley (Lower Valais)
Landform(s): Talus slope



GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
02*	2720	2.87	2.38
03*	2690	1.76	1.09
04*	2660	0.83	–0.28
05*	2665	1.35	–0.13
09	2750	2.13	n.a.
11	2710	1.99	1.31
13	2705	2.94	2.48
20	2695	1.68	0.94
21	2675	–0.62	–1.40
22	2640	–0.68	–1.67

* long-term series used for the calculation of mean values



Mean values since start of series

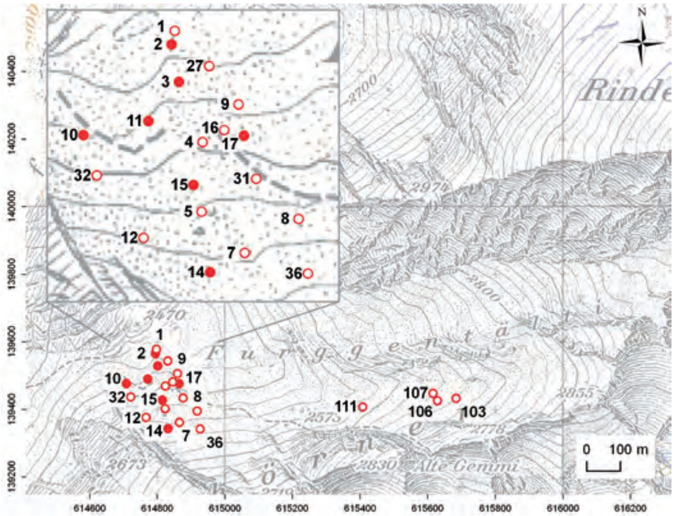
MAGST	+0.90°C
Snow free date	18. Jun
Ground Freezing Index	–493 °C.d
Ground Thawing Index	+808 °C.d

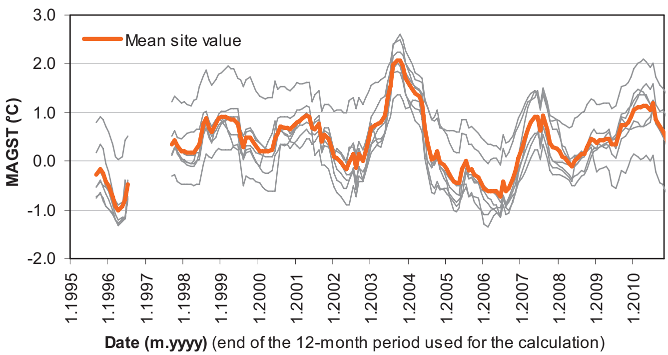
Trend (until 2009/10) of mean values

	since 1998/99	since 1999/00	since 2001/02
MAGST (°C/year)	n.a.	n.a.	–0.00
Snow free date (day/year)	n.a.	n.a.	+1.0
Ground Freezing Index (°C/year)	n.a.	n.a.	+8.3
Ground Thawing Index (°C/year)	n.a.	n.a.	–10.6

GST Gemmi

Region: Gemmipass (Upper Valais)
Landform(s): Rock glacier, talus slope





GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
01	2452	1.64	1.19
02*	2455	–0.24	–0.49
03*	2469	0.92	0.71
04	2494	1.10	1.15
05	2519	0.45	–0.27
07	2529	–0.94	–0.47
08	2520	1.95	1.53
09	2467	0.94	0.67
10*	2473	0.43	0.58
11*	2479	0.87	0.70
12	2528	0.84	–0.06
14*	2536	0.58	0.64
15*	2511	n.a.	1.00
16	2486	n.a.	1.56
17*	2488	1.50	1.54
27	2457	1.12	1.03
31	2504	0.77	n.a.
32	2492	1.76	1.30
36	2549	0.65	0.86
103	2653	–0.31	–0.28
106	2640	0.05	0.41
107	2636	0.35	0.80
111	2586	0.12	0.76

* long-term series used for the calculation of mean values

Mean values since start of series

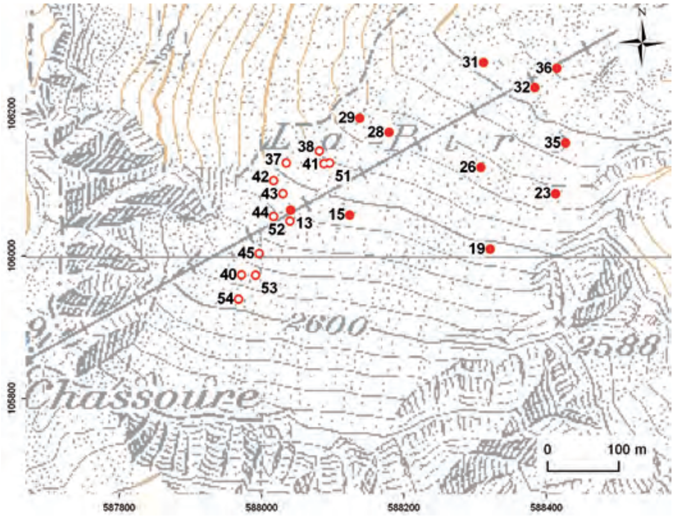
MAGST	+0.44 °C
Snow free date	18. Jun
Ground Freezing Index	–544 °C.d
Ground Thawing Index	+683 °C.d

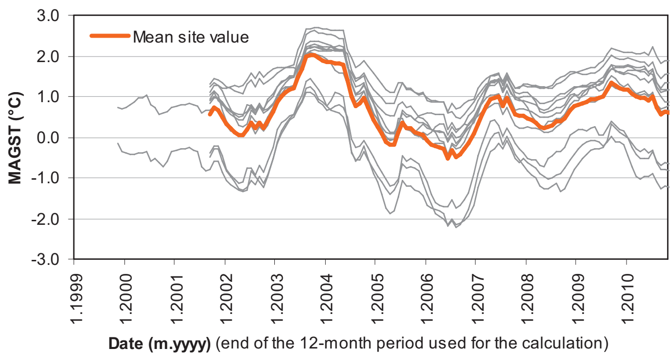
Trend (until 2009/10) of mean values

	since 1998/99	since 1999/00	since 2001/02
MAGST (°C/year)	–0.01	–0.01	+0.01
Snow free date (day/year)	–1.7	–1.0	–0.8
Ground Freezing Index (°C/year)	–21.0	–16.3	–1.1
Ground Thawing Index (°C/year)	+18.8	+20.3	+16.7

GST Lapires

Region: Nendaz Valley (Lower Valais)
Landform(s): Talus slope





GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
13*	2515	0.31	–0.79
15*	2510	1.28	0.62
19*	2505	1.52	0.69
23*	2445	2.19	1.83
26*	2445	1.78	1.30
28*	2450	1.77	1.10
29*	2450	1.69	1.16
31*	2390	2.02	1.46
32*	2390	1.66	0.99
35*	2410	0.03	–1.26
36*	2375	0.37	–0.69
37	2490	0.53	–0.09
38	2480	–0.18	–0.96
40	2575	under proc.	
41	2485	under proc.	
51	2484	under proc.	
52	2526	under proc.	
53	2568	under proc.	
54	2590	under proc.	

* long-term series used for the calculation of mean values

Mean values since start of series

MAGST	+0.65 °C
Snow free date	20. Jun
Ground Freezing Index	-441 °C.d
Ground Thawing Index	+685 °C.d

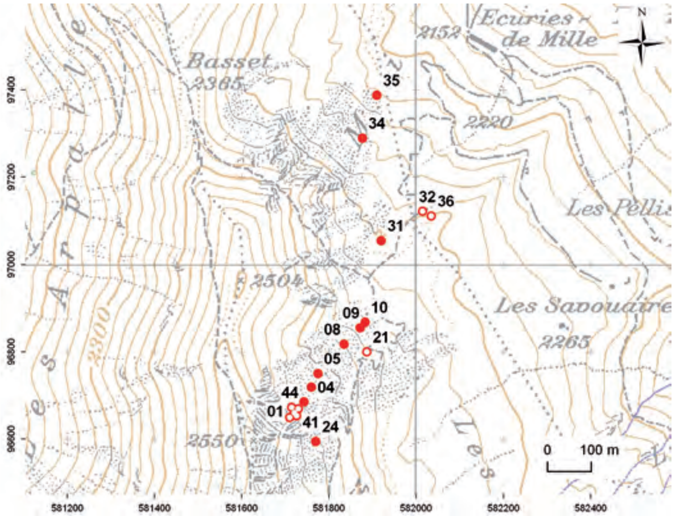
Trend (until 2009/10) of mean values

	since 1998/99	since 1999/00	since 2001/02
MAGST (°C/year)	n.a.	n.a.	0.0
Snow free date (day/year)	n.a.	n.a.	+0.2
Ground Freezing Index (°C/year)	n.a.	n.a.	+3.0
Ground Thawing Index (°C/year)	n.a.	n.a.	+0.9

GST Alpage de Mille

Region: Bagnes Valley (Lower Valais)

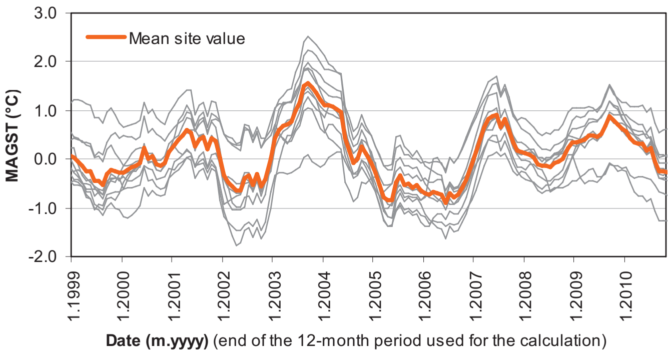
Landform(s): Rock glacier, debris terrain with soil development



GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
01	2450	2.46	2.27
02	2430	2.94	2.17
03*	2418	0.83	–0.38
04*	2410	0.86	–0.20
05*	2405	0.96	0.09
08*	2378	1.49	0.55
09*	2355	0.89	–0.38
10*	2340	–0.12	–0.67
21	2365	2.14	1.62
24*	2445	1.54	–0.31
31*	2303	1.20	–0.08
32	2292	2.28	1.74
34*	2260	1.19	0.02
35*	2230	–0.07	–1.26
36	2300	1.71	1.09
41	2435	2.83	2.81
43	2435	3.56	3.16
44	2435	3.32	2.59

* long-term series used for the calculation of mean values



Mean values since start of series

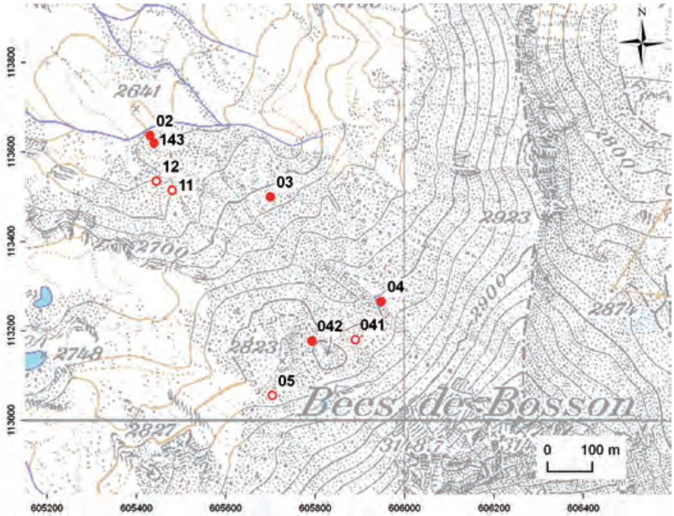
MAGST	+0.1 °C
Snow free date	04. Jun
Ground Freezing Index	–747 °C.d
Ground Thawing Index	+773 °C.d

Trend (until 2009/10) of mean values

	since 1998/99	since 1999/00	since 2001/02
MAGST (°C/year)	+0.02	+0.01	0.00
Snow free date (day/year)	+0.2	–0.1	+0.5
Ground Freezing Index (°C/year)	+5.1	+5.5	–0.4
Ground Thawing Index (°C/year)	–1.0	–2.0	–1.0

GST Réchy – Becs de Bosson

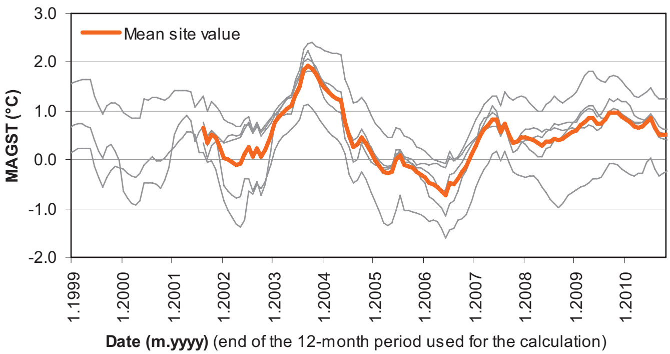
Region: Réchy Valley (Lower Valais)
Landform(s): Rock glacier



GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
001*	2450	2.46	2.27
002*	2650	1.26	0.45
003*	2720	–0.07	–0.32
004*	2803	1.70	1.24
005	2805	1.96	1.38
011	2659	n.a.	n.a.
012	2642	n.a.	n.a
041	2803	1.21	1.12
042*	2805	1.00	0.68
143*	2665	0.96	0.56

* long-term series used for the calculation of mean values



Mean values since start of series

MAGST	+0.46 °C
Snow free date	12. Jun
Ground Freezing Index	–447 °C.d
Ground Thawing Index	+620 °C.d

Trend (until 2009/10) of mean values

	since 1998/99	since 1999/00	since 2001/02
MAGST (°C/year)	n.a.	n.a.	–0.02
Snow free date (day/year)	n.a.	n.a.	+0.1
Ground Freezing Index (°C/year)	n.a.	n.a.	–3.7
Ground Thawing Index (°C/year)	n.a.	n.a.	–7.5

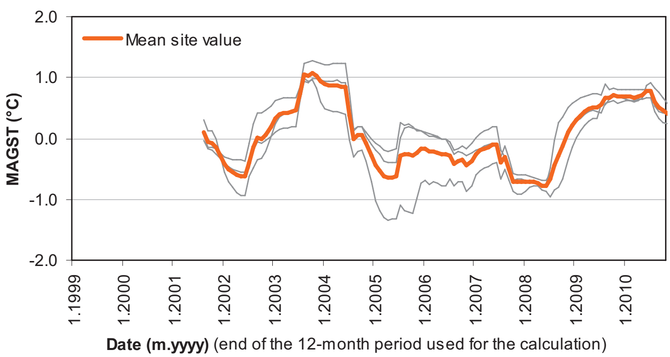
GST Réchy – Tsavolires

Region: Réchy Valley (Lower Valais)
Landform(s): Talus slope

GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
06	2795	2.42	1.89
07*	2804	0.80	0.43
08*	2822	0.60	0.32
09*	2850	0.64	0.76

* long-term series used for the calculation of mean values



Mean values since start of series

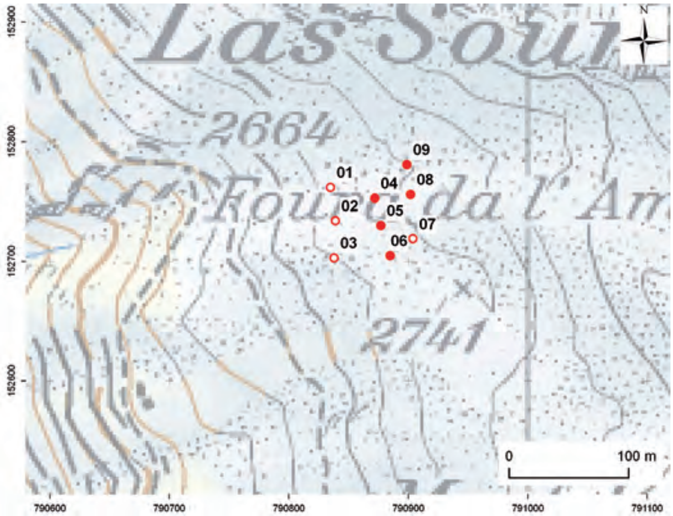
MAGST	+0.03 °C
Snow free date	16. Jul
Ground Freezing Index	–255 °C.d
Ground Thawing Index	+284 °C.d

Trend (until 2009/10) of mean values

	since 1998/99	since 1999/00	since 2001/02
MAGST (°C/year)	n.a.	n.a.	–0.01
Snow free date (day/year)	n.a.	n.a.	+0.1
Ground Freezing Index (°C/year)	n.a.	n.a.	+1.3
Ground Thawing Index (°C/year)	n.a.	n.a.	–1.8

GST Schafberg – Foura da l'Amd Ursina

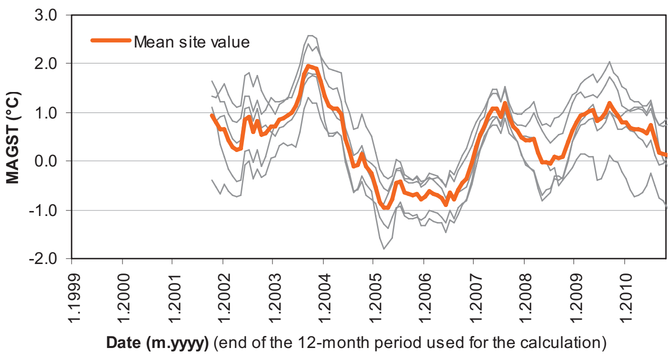
Region: Upper Engadine GR (Pontresina, Foura da l'Amd Ursina)
Landform(s): Rock glacier



GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
01	2722	1.63	0.04
02	2723	n.a.	n.a.
03	2720	n.a.	1.93
04*	2730	1.02	0.73
05*	2730	1.72	0.29
06*	2730	2.05	0.74
07	2740	n.a.	n.a
08*	2740	1.03	–0.09
09*	2740	0.12	–0.75

* long-term series used for the calculation of mean values



Mean values since start of series

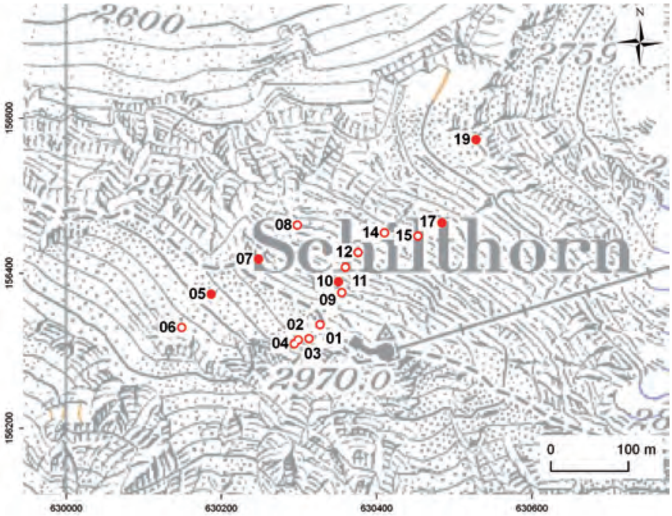
MAGST	+0.41 °C
Snow free date	31. May
Ground Freezing Index	–727 °C.d
Ground Thawing Index	+887 °C.d

Trend (until 2009/10) of mean values

	since 1998/99	since 1999/00	since 2001/02
MAGST (°C/year)	n.a.	n.a.	0.0
Snow free date (day/year)	n.a.	n.a.	–0.3
Ground Freezing Index (°C/year)	n.a.	n.a.	0.3
Ground Thawing Index (°C/year)	n.a.	n.a.	–16.8

GST Schilthorn

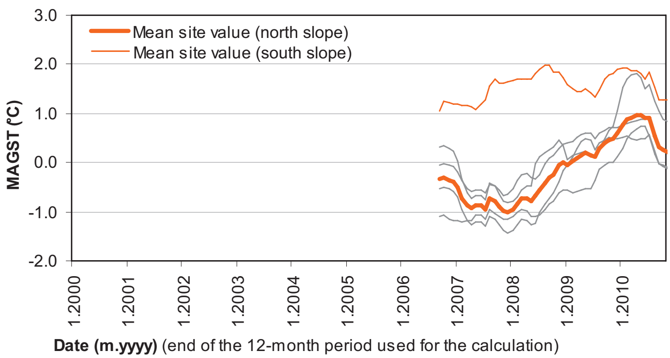
Region: Lauterbrunnen Valley (Bernese Oberland)
Landform(s): Debris mantled terrain, crest



GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
01	2956	–0.21	–0.16
02	2954	0.49	0.30
03	2948	n.a.	n.a.
04	2941	n.a.	–0.33
05*	2906	1.69	1.28
06	2873	n.a.	1.76
07*	2933	–0.05	–0.03
08	2882	-1.15	–0.57
09	2926	-0.14	–0.46
10*	2927	0.46	–0.01
11	2915	0.46	0.48
12	2902	n.a.	n.a.
14	2875	n.a.	0.63
15	2859	0.21	0.40
17*	2837	0.66	0.33
19*	2787	0.49	1.04

* long-term series used for the calculation of mean values

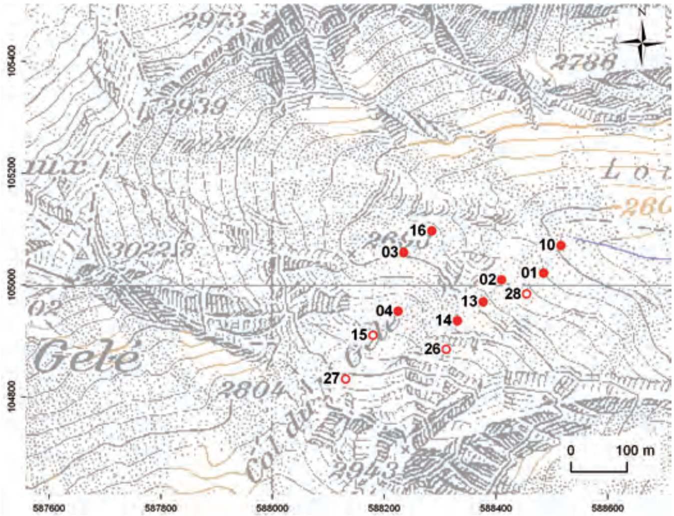


Mean values since start of series

MAGST	–0.16 °C
Snow free date	30 Jun
Ground Freezing Index	–439 °C.d
Ground Thawing Index	+386 °C.d

GST Yettes Condja

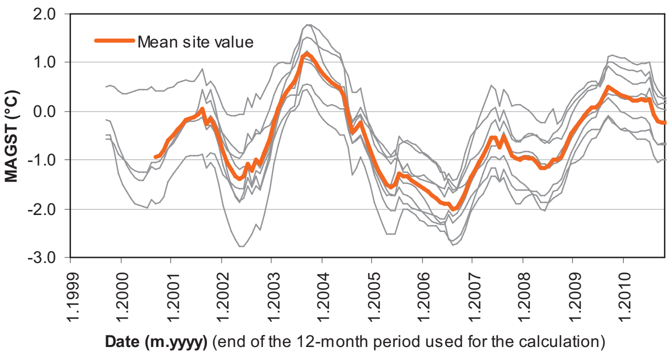
Region: Nendaz Valley (Lower Valais)
Landform(s): Rock glacier



GST sites and MAGST

ID	Elev. (m a.s.l.)	08/09 (°C)	09/10 (°C)
01*	2630	1.12	0.44
02*	2660	–0.10	–0.67
03*	2705	0.49	–0.23
04*	2750	0.28	–0.69
10*	2600	–0.11	–1.05
13*	2690	0.93	0.14
14*	2715	0.37	0.08
15	2755	–1.41	–1.55
16*	2685	1.01	0.30
26	2740	0.60	0.51
27	2810	0.26	–0.18
28	2650	2.42	1.53

* long-term series used for the calculation of mean values



Mean values since start of series

MAGST	–0.55 °C
Snow free date	6. Jul
Ground Freezing Index	–598 °C.d
Ground Thawing Index	+411 °C.d

Trend (until 2009/10) of mean values

	since 1998/99	since 1999/00	since 2001/02
MAGST (°C/year)	n.a.	n.a.	–0.02
Snow free date (day/year)	n.a.	n.a.	–0.4
Ground Freezing Index (°C/year)	n.a.	n.a.	–6.3
Ground Thawing Index (°C/year)	n.a.	n.a.	–9.8

PERMOS Kinematics Sites

Table A.4: Rock glaciers where terrestrial surveys are conducted.

Site	Region	Aspect	Elevation (m a.s.l.)	Start	Institution
Aget	Lower Valais	SE	2810–2890	2001	UniFR
Alpage de Mille	Lower Valais	NE	2230–2450	2009	UniFR
Gemmi	Bernese Oberland	N	2450–2650	1994	UniBE
Grosses Gufer	Bernese Oberland	NW	2360–2600	2007	UniFR
Hungerlitälli 1	Lower Valais	NNW	2630–2780	2001	UZH
Hungerlitälli 3	Lower Valais	NW	2515–2650	2002	UZH
Lapires	Lower Valais	NNE	2640–2610	2007	UniFR
Yettes Condjà B	Lower Valais	NE	2600–2740	2000	UniL
Yettes Condjà C	Lower Valais	NE	2620–2820	2000	UniL
Monte Prosa A	Ticino	N	2430–2600	2009	UniFR
Monte Prosa B	Ticino	WNW	2450–2520	2009	UniFR
Murtèl	Engadine	NW	2630–2800	2009	UZH
Muragl	Engadine	NW	2490–2750	2009	UZH
Réchy	Lower Valais	NW	2610–2850	2001	UniFR
Stabbio di Largario	Ticino	N	2240–2550	2009	UniL
Tsarmine	Lower Valais	W	2460–2640	2004	UniFR/UniL
Valle di Sceru	Ticino	NE	2450–2550	2009	UniL

Air Photos

Table A.5: Rock glacier areas where air photos are acquired regularly since 1980 for systematic monitoring of creep (low flying height (low f. h.), black and white (b-w)).

Region	Type	Available years
Gemmi/Furggent.	low f. h., b-w	1990, 1995, 1999, 2000, 2001, 2003, 2007, 2010
Grosses Gufer	low f. h., b-w	1987, 1994, 2000, 2008
Gruben	low f. h., b-w	1967, 1975, 1983, 1985, 1988, 1989, 1990, 1991, 1992, 1994, 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2008, 2010
Murtèl	low f. h., b-w	1987, 1988, 1991, 1995, 1996, 2002, 2007
Muragl	low f. h., b-w	1981, 1985, 1990, 1994, 1998, 1999, 2000, 2002, 2007
Réchy	low f. h., b-w	1986, 1991, 1995, 1999, 2004, 2008
Schafberg	low f. h., b-w	1991, 1994, 1998, 1999, 2000, 2007
Suvretta	low f. h., b-w	1992, 1997, 2002, 2007