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2004/2005 and 2005/2006

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Permafrost Monitoring Switzerland

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View from the Augstbordpass (2894 m a.s.l.) over various rock glaciers in the Augstbordtälli (Matter Valley) to the south east. Photo: I. Gärtner-Roer, 2003.

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Reporting Period	*Report No.*	*Year*
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

Preface

The present report covers the period after the extreme summer 2003, i.e. from 2004 to 2006. In summer 2003 a rock fall blocked some 90 climbers in the most popular route to the Matterhorn summit. They were rescued by helicopter, and the story ran around the world. Five days later, we welcomed the worldwide scientific permafrost community to the 8th International Conference on Permafrost in Zurich. It was at this time, when, after three years of being officially established, PERMOS extended its pilot phase until the end of 2006 to refine and adapt the parameters monitored. Thus, this report is the last one of the PERMOS pilot phase. Similarly to the stages of PERMOS, we will evaluate and re-organize the structure of the report for the next period 2006–2008.

Some 5 years later, at the time the 9th International Conference on Permafrost (NICOP) was held in Fairbanks (Alaska), the Swiss Federal Council approved a request by the Federal Department of Home Affairs (prepared by the Swiss GCOS Office at the Federal Office of Meteorology and Climatology MeteoSwiss), which will provide finances to assure long-term continuation of at-risk climate measurement series. Most of the so-called essential climate variables (ECV), e.g., air temperature, precipitation, are being monitored based on legal regulations. However, no such regulation has existed so far for the three variables of the cryosphere: snow (partially), glaciers, and permafrost. Based on this high-level decision, the continuation of PERMOS is secured for the period after the contract for 2007–2010 between by the Academy of Sciences (SCNAT), the Federal Office for the Environment (FOEN), and the Federal Office of Meteorology and Climatology MeteoSwiss.

Three of the items mentioned above merit discussion:

(1) The niche out of which the Matterhorn rock fall came from has been equipped with intelligent sensors for temperature, water/ice pressure and dilatation, which communicate wirelessly through a base station. The data can be accessed online via the internet. It is the highly interdisciplinary research project PermaSense, a show case within the NCCR Mobile Information and Communication Systems (MICS), which uses the interaction of computer scientists, technicians, and permafrost researchers to elaborate a new and reliable generation of sensors. This is an excellent example that shows the outreach of PERMOS, and there are fortunately more examples where a fruitful collaboration led to mutual success.

(2) Even though the reporting in media may sometimes be unobjective, it is a fact that topics such as climate change, hazards or permafrost benefit through articles and contributions in media. It is, once more, important to find a good relation to journalists, and it is of mutual benefit if the scientific content is correct but understandable to the greater public.

(3) Finally, after the pilot phase we have collected major experiences on how to monitor permafrost in terms of both, science and technology. The PERMOS community contributed to a thorough

evaluation of the monitoring strategy, observed parameters, and all PERMOS sites. The results were presented in a contribution at the NICOP.

It is a pleasure to look back to the development of the Network of the Swiss Permafrost Monitoring. It is not just SCNAT, FOEN, and MeteoSwiss, who help financing PERMOS, but in particular the long-lasting and benevolent collaboration among the six academic partner institutions that facilitated the success of PERMOS. Many thanks to all who contributed to this!

January 2009, Dani Vonder Mühll

Summary

The present report covers the period from October 2004 to September 2006. It is the last report of the pilot phase 2000–2006 of the network for permafrost monitoring in Switzerland (PERMOS). At this point, PERMOS includes (a) 11 drill sites (including 22 boreholes and geophysical monitoring at 4 of the sites), (b) 11 surface temperature sites (including measurements in loose debris at 9 sites, in bedrock at 5 sites, and at the bottom of the snow cover (BTS) at 3 sites), and (c) aerial photographs taken by Swisstopo.

Winter 2004/2005 was characterized by an early and thin snow cover in the higher alpine regions and an early snow melt in spring. A long phase of above average air temperatures followed, which lasted until July and made summer 2005 the second warmest on record. Winter 2005/2006 started late, had a long lasting thick snow cover, and was followed by a warm summer with the hottest July ever measured.

Active layer thicknesses in summer 2004 were similar to those before 2003 at most sites. Hence, thermal changes in the subsurface from the 2003 heat wave were not sustained, although the ice content at the permafrost table may have been permanently modified. The active layer deepened again in several boreholes in summer 2005, reaching values similar to 2003, and remained more or less stable in summer 2006. At ca. 10 m depth, ground temperatures at the drill sites displayed a warming until the beginning of 2005, which results from the preceding heat period in summer 2003. Then, mainly as a result of the snow conditions in winter, a cooling period followed. Since 2005, temperature observations are complemented by electrical resistivity tomography (ERT) measurements at 4 drill sites to monitor physical properties of the ground (e.g., ice content or unfrozen water content). The ERT monitoring strategy is outlined and discussed in this report.

Ground surface temperatures (GST) were low in both years of the reporting period, especially during winter. In 2005, GST temporarily dropped to new minima and reached about mean values of the past decade at the end of the reporting period. Rock surface temperatures (RST) were integrated into PERMOS in summer 2004 and are presented and discussed in detail in this report. Temperature values in steep rock clearly display the cold conditions in winter 2004/2005 as well as the warm summer 2006.

The chapter on special aspects of permafrost monitoring is dedicated to the observed acceleration of rock glaciers in the past two decades. The destabilization of several landforms shows that permafrost creep conditions in the Alps are changing.

In general, both, surface temperatures and ground temperatures in the uppermost meters decreased to pre-2003 conditions at all sites during the reporting period, which is mainly a result of the snow conditions.

Zusammenfassung

Der vorliegende Bericht deckt die Periode Oktober 2004 bis September 2006 ab und ist der letzte Bericht der Pilot-Phase 2000–2006 des Permafrost Messnetztes der Schweiz (PERMOS). Zurzeit umfasst PERMOS (a) 11 Bohrlochstandorte (inkl. 22 Bohrlöcher und Geophysik Monitoring an 4 Standorten), (b) 11 Gebiete mit Messungen der Oberflächentemperatur (an 10 Standorten in losem Material, an 5 im Fels und an 3 an der Basis der Schneedecke (BTS)) und (c) Luftbildaufnahmen der Swisstopo.

Der Winter 2004/2005 ist charakterisiert durch eine frühe und dünne Schneedecke in den hochalpinen Regionen und eine frühe Schneeschmelze im Frühling. Darauf folgten eine lange Phase mit überdurchschnittlichen Lufttemperaturen bis im Juli 2005 und der zweitwärmste je gemessene Sommer. Der Winter 2005/2006 setzte spät ein und hatte eine lange anhaltende dicke Schneedecke. Wiederum folgte ein warmer Sommer, im Jahr 2006 mit dem heissesten je registrierten Juli.

Die Auftauschichten vom Sommer 2004 waren an den meisten Standorten ähnlich tief wie vor 2003. Die thermischen Effekte der Hitzewelle 2003 im Untergrund waren somit nicht von langer Dauer, der Eisgehalt am Permafrostspiegel kann allerdings nachhaltig verändert sein. Die Auftauschichten vom Sommer 2005 waren in einigen Bohrlöchern wieder ähnlich mächtig wie 2003 und jene vom Sommer 2006 blieben mehr oder weniger stabil. Die Bohrlochtemperaturen in ca. 10 m Tiefe stiegen 2004 bis zum Beginn des Jahres 2005 immer noch als Folge der Hitzeperiode 2003. Als Reaktion auf die Schneeverhältnisse im Winter folgte dann eine Abkühlung. Seit 2005 werden die Temperaturmessungen an 4 Bohrlochstandorten durch Elektrische Widerstands Tomographie (ERT) ergänzt, um physikalische Eigenschaften im Untergrund (Eisgehalt und ungefrorener Wassergehalt) zu beobachten. Die Strategie des ERT-Monitoring wird in diesem Bericht beschrieben und diskutiert.

Die Oberflächentemperaturen (GST) waren in den beiden Berichtsjahren tief, besonders im Winter. Im Jahr 2005 fielen sie vorübergehend auf neue Tiefstwerte und erreichten gegen Ende der Berichtsperiode wieder Durchschnittswerte der letzten beiden Jahrzehnte. Felsoberflächentemperaturen wurden 2004 in PERMOS aufgenommen und werden in diesem Bericht beschrieben und diskutiert. Die Werte in steilen Felswänden zeigen deutlich die kalten Bedingungen im Winter 2004/2005 sowie den warmen Sommer 2006.

Das Kapitel zu ausgewählten Aspekten des Permafrostmonitorings widmet sich der beobachteten Beschleunigung der Blockgletscher in den letzten zwei Jahrzehnten. Die Destabilisierung verschiedener Formen zeigt, dass sich die Kriechverhältnisse des Permafrosts in den Alpen verändern.

Generell sind während der Berichtsperiode Oberflächentemperaturen und Temperaturen in den obersten Metern wieder auf die Verhältnisse von vor 2003 gesunken, was hauptsächlich eine Folge der Schneeverhältnisse ist.

Résumé

Ce rapport couvre la période d'octobre 2004 à septembre 2006. Il s'agit du dernier rapport de la phase pilote (6 ans) du réseau de monitoring du pergélisol en Suisse (PERMOS). A ce jour, PERMOS comprend (a) 11 sites de forage (incluant 22 forages et 4 installations de monitoring géophysique), (b) 10 sites de mesure de température de surface (incluant des 10 sites sur débris meubles, 5 sites d'observation sur roche en place, et 3 sites de mesure de la température à la base du manteau neigeux (BTS)) et (c) des photographies aériennes prises par Swisstopo.

L'hiver 2004/2005 fut caractérisé fin dans les hautes régions alpines par un enneigement précoce mais qui demeura peu important, ainsi que par une fonte précoce de la neige au printemps. Une longue phase de températures de l'air élevées suivit jusqu'en juillet et fit de l'été 2005 le second été le plus chaud enregistré. L'hiver 2005/2006 débuta tardivement, mais connut ensuite un enneigement important et durable. Il fut suivi d'un été chaud, dont le mois de juillet fut le plus chaud jamais mesuré.

Les épaisseurs de couche active observées en 2004 furent similaires à celles d'avant 2003 sur la plupart des sites. A faible profondeur, les changements thermiques induits par la canicule de 2003 n'avaient pas perduré, bien que la teneur en glace au niveau de la toit du permafrost puisse avoir été modifiée de manière permanente. L'épaisseur de la couche active augmenta à nouveau dans plusieurs forages durant l'été 2005, atteignant des valeurs similaires à 2003, et resta plus ou moins stable en 2006. A environ 10 m de profondeur, les températures du sol subirent un réchauffement jusqu'au début 2006, conséquence de la période chaude de 2003. Ensuite, principalement en raison des conditions d'enneigement hivernales, une phase de refroidissement débuta. Depuis 2005, les observations de température sont complétées par des mesures de tomographie de résistivité électrique (ERT) sur 4 sites de forage afin de suivre les variations des propriétés physiques du sol (i.e. teneur en glace ou teneur en eau non gelée). La stratégie du monitoring ERT est décrite et discutée dans ce rapport.

Les températures de surface (GST) furent basses durant les deux années du rapport, particulièrement durant les hivers. En 2005, les températures annuelles atteignirent temporairement de nouveaux minima. Elles étaient proches des valeurs moyennes de la décennie écoulée à la fin de la période du rapport. L'observation des températures de surface des zones rocheuses (RST) a été intégrée dans PERMOS en été 2004. Elles sont présentées et discutées en détail dans ce rapport. Dans les parois raides, les valeurs reflétèrent les conditions froides de l'hiver 2004/2005 ainsi que celles de l'été chaud de 2006.

Le chapitre sur les aspects particuliers du monitoring du pergélisol est consacré à l'accélération des glaciers rocheux qui s'est produite durant les deux dernières décennies. La déstabilisation de plusieurs formes montre que les conditions de fluage du pergélisol se modifient.

En général durant la période de rapport, tant les températures de surface que les températures du sol dans les premiers mètres de profondeur ont diminué jusqu'à des conditions pré-2003, une évolution essentiellement due aux conditions d'enneigement.

Riassunto

Questo rapporto copre il periodo da ottobre 2004 a settembre 2006. Si tratta dell'ultimo rapporto della fase-pilota di sei anni della rete di monitoraggio del permafrost in Svizzera (PERMOS). Al momento, PERMOS comprende (a) 11 siti di perforazione (comprendenti 22 perforazioni profonde e 4 siti di monitoraggio geofisico del luogo di perforazione), (b) 11 siti di monitoraggio delle temperature della superficie del suolo (comprendenti 10 siti di misura su sedimenti sciolti, 5 su roccia madre e 3 alla base del manto nevoso (BTS)), e (c) fotografie aeree scattate da Swisstopo.

Nelle regioni di alta montagna, l'inverno 2004/2005 è stato caratterizzato da un innevamento precoce e assai scarso e dallo scioglimento anticipato del manto nevoso in primavera. Ne è seguita una lunga fase di temperature dell'aria superiori alla media, durata fino a luglio, che ha fatto sì che l'estate 2005 sia stata la seconda estate più calda mai misurata. L'inverno 2005/2006 è cominciato assai tardivamente, ha presentato una copertura nevosa spessa e duratura, ed è stato seguito da un'estate calda, caratterizzata dal mese di luglio più caldo mai misurato.

Lo spessore dello strato attivo durante l'estate del 2004 è stato, in molti siti, simile a quello misurato prima del 2003. I cambiamenti termici del sottosuolo dovuti alla canicola del 2003, quindi, non si sono rivelati permanenti, sebbene questi potrebbero avere modificato in maniera duratura il tenore in ghiaccio al tetto del permafrost. Lo spessore dello strato attivo è aumentato in maniera importante in parecchie perforazioni profonde nell'estate del 2005, raggiungendo dei valori simili a quelli del 2003, mentre è rimasto assai stabile nell'estate del 2006. A circa 10 m di profondità, le temperature del sottosuolo si sono riscaldate a partire dall'inizio del 2005 come conseguenza del periodo canicolare del 2003. Quindi, principalmente come conseguenza delle condizioni di innevamento invernali, è seguito un periodo marcato dal raffreddamento delle temperature del sottosuolo. Dal 2005, il monitoraggio delle temperature è completato dalle misure di tomografia delle resistività elettriche (ERT) in quattro siti di perforazione, e questo alfine di monitorare le proprietà fisiche del terreno (come, ad esempio, il tenore in ghiaccio o il tenore in acqua allo stato liquido). La strategia di monitoraggio ERT è presentata e discussa in questo rapporto.

Le temperature della superficie del suolo (GST) sono state abbastanza basse in tutti gli anni del periodo studiato, in particolare durante l'inverno. Durante il 2005, GST è scesa temporaneamente ai nuovi minimi storici e ha raggiunto, alla fine del periodo studiato, i valori medi dell'ultimo decennio. Le temperature di superficie degli affioramenti rocciosi sono state integrate a PERMOS durante l'estate del 2004 e sono presentate e discusse in questo rapporto. I valori misurati nelle pareti rocciose hanno registrato chiaramente le condizioni fredde dell'inverno 2004/2005, così come le condizioni calde dell'estate del 2006.

Il capitolo sugli aspetti particolari del monitoraggio del permafrost è dedicato all’accelerazione dei rock glaciers negli ultimi vent’anni. La destabilizzazione di parecchi rock glaciers permette di fare l’ipotesi che le condizioni di reptazione del permafrost nelle Alpi stanno cambiando.

In generale, per il periodo coperto da questo rapporto, sia le temperature della superficie del suolo che quelle dei primi metri del sottosuolo sono evolute in tutti i siti di misura verso delle condizioni simili a quelle che regnavano prima del 2003. Questa evoluzione risulta principalmente dalle condizioni di innevamento durante gli inverni studiati.

Resumaziun

Quest rapport resumescha la perioda digl october 2004 entochen il settember 2006 ed ei il davos rapport dils 6 onns da fasa da pilot dalla reit da mesiraziun da schelira permanenta en Svizra PERMOS. La reit consista ussa ord (a) 11 posts da mesiraziun (cun 22 foras da sondagi e surveglionza geofisicala a 4 da quels posts), (b) 11 regiuns nua che la temperetura dalla surfatscha vegn mesirada continuadamein (en 10 da quellas vegn la temperatura era mesirada en la glera, en 5 el crap ferm ed en 3 loghens al funs dalla cozza da neiv (BTS)), e finalmein fotografias ord l'aria dalla Swisstopo.

Igl unviern 2004/2005 ei staus caracterisaus tras ina fina cozza da neiv ellas regiuns pli aultas baul igl atun e buna aura cun luada da neiv baul la primavera. Silsuenter ha ei dau ina liunga fasa da temperaturas dalla aria fetg aultas, la quala ha teniu entochen il fenadur, aschia che la stad 2005 ei stada la secunda pli caulda stad dapli che las temperaturas vegnan registradas. Igl unviern 2005/2006 ha entschiet tard, mo ha persuenter era giu ina grossa cozza da neiv che ha teniu ditg. Igl unviern ei staus suandaus dad ina fetg caulda stad cul pli cauld fenadur dapli che las temperaturas vegnan mesiradas.

La grossezia dalla rasada da sdregliada la stad 2004 ei stada pil semeglionta a quellas da avon igl onn 2003. Il disturbi termal dalla unda da calira digl onn 2003 ei aschia buca staus da liung cuoz. Tuttina savess il cuntegn da glatsch el livel da schelira permanenta esser alteraus durablamein. Las rasadas da sdregliada dalla stad 2005 en entginas foras ein puspei stadas tuttina profundas sco igl onn 2003 ed ein stadas pli u meins stabilas duront la stad 2006. Las temperaturas en ca. 10 meters profunditad ein aunc carschidas naven dil 2004 entochen l'entschatta digl onn 2005 sco consequenza dalla perioda da calira digl onn 2003. Sco reacziun sin las condiziuns da neiv egl unviern ei lu seresultau ina sfradentada. Naven digl onn 2005 vegnan las mesiraziuns da temperaturas en 4 foras cumpletadas entras tomografia da resistenza electrica (Electrical Resistivity Tomography ERT). Aschia eis ei ussa pusseivel da survegliar ed d'intercurir las caracteristicas fisicalas el fundament (cuntegn da glatsch ed aua). La strategia da surveglionza cun ERT vegn messa avon e discutada en quest rapport.

Las temperaturas alla surfatscha (GST) ein stadas bassas en omisduas periodas da raport, oravontut duront igl unviern. Egl onn 2005 ein ellas curdadas temporariamein sin temperaturas las pli bassas, sisuenter puspei ella media dils davos dus decenis. La collecziun dallas temperaturas dalla surfatscha dil grep ein part da PERMOS naven digl onn 2004 e vegnan era messas avon e discussiunadas en quest rapport. Las temperaturas en preits crap fetg teissas ei in clar mussament per las relaziuns fetg freidas digl unviern 2004/2005, sco era dalla caulda stad 2006.

Il capetel sur dils aspects dalla surveglionza da schelira permanenta sefitschentescha cun l'acceleraziun dalla sdregliada dils glatschers da schelira permanenta duront ils davos dus decenis. La destabilisaziun da differentas formaziuns muossa che il ruschnar dalla schelira permanenta en las Alps semida.

En general ei semussa che las temperaturas da surfatscha ed els emprems meters dil fundament duront l'entira perioda da raport ein idas anavos sin las relaziuns da avon igl onn 2003. La raschun pli impurtonta per quella reducziun ein las relaziuns da neiv stadas.

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1 Introduction

End of the 6-year Pilot Phase of PERMOS

The present report is the last one of a series of three reports covering the 6-year pilot phase of the monitoring network for permafrost in Switzerland (PERMOS), which started in the year 2000. The monitoring of the three key elements borehole temperatures, ground surface temperatures, and aerial photographs proved effective. The methodology used is well established and this methodology will be continued.

A thorough evaluation of the monitoring strategy, standards, reports, and sites took place at the beginning of the operational service of PERMOS in 2007. Results will be published and considered in the coming reports. However, sites no longer belonging to the network, are not included in the present report. New boreholes are also not presented here due to the short data series. In this report, we present data from 22 boreholes at 11 sites, 11 surface temperature sites (at 10 sites temperatures were measured in debris or blocks, at 5 sites in rock, and at 3 sites at the bottom of the snow cover). The number of measurement sites for ground surface temperature (GST) remained constant. Air photos were taken of one site.

After the completion of a pilot study at Schilthorn (cf. Chapter 7, Glaciological Report Permafrost, No. 4/5), a geophysical monitoring programme was set up in the year 2005 in order to systematically observe ice content or unfrozen water content at the borehole sites and complement temperature measurements. The first two years of results are presented in this report, along with a detailed description and discussion of the monitoring system.

In the summers of 2003 and 2004 rock surfaces with different inclinations and aspects were instrumented to observe near surface temperatures at a number of surface temperature measurement sites (cf. Chapter 4, Glaciological Report Permafrost, No. 4/5). First data series and monitoring experience are now available. As with the ERT monitoring, rock surface temperatures (RST) are presented and discussed in more detail in this report.

The recent acceleration of rock glaciers in the Swiss Alps was introduced in the last report (cf. Chapter 7, Glaciological Report Permafrost, No. 4/5). Because the subject is increasingly important and because PERMOS intends to extend its activity to monitor permafrost dynamics, the section on special aspects of permafrost monitoring is dedicated to rock glacier dynamics.

The following PERMOS partner institutes are responsible for field work, site maintenance, and data processing for the present report:

- University of Zurich: Department of Geography, Glaciology, Geomorphodynamics & Geochronology (GIUZ), host of the PERMOS Office
- ETH Zurich: Institute for Geotechnical Engineering (IGT-ETH)

- University of Berne: Department of Geography (GIUB)
- University of Fribourg: Department of Geosciences, Geography Institute (IGUF)
- University of Lausanne: Faculty of Earth Science and Environment, Geography Institute (IGUL)
- WSL Institute for Snow and Avalanche Research Davos (SLF)

Photo 1: Rock glacier Yettes Condjà – a PERMOS GST site. Photo: C. Lambiel.

2 Weather and Climate

The summer temperatures and the snow conditions during winter are two of the crucial parameters governing the thermal state of permafrost. Snow has a strong insulating effect by decoupling the ground thermally from the atmosphere. Therefore the time of the first snowfall in autumn, the snow thickness, and the time when the terrain becomes snow free in spring play decisive roles: If the first large snowfall in autumn takes place before the active layer freezes, the summer heat stored in the subsurface is preserved during wintertime, causing higher ground temperatures. In case the snow falls after the refreezing of the active layer, heat transferred out of the ground leads to lower ground temperatures. The time in spring when the terrain becomes snow free is important, because from this point atmospheric conditions are more strongly influencing the ground temperatures. In steep rock faces without any thicker snow cover air temperatures influence near surface temperatures during the whole year.

2.1 Weather and Climate in 2004/2005

Both the weather and the climate data are based on the reports by the Federal Office of Meteorology and Climatology MeteoSwiss (MeteoSwiss, 2004, 2005). The snow data originate from SLF.

Weather and climate conditions in the hydrological year 2004/2005
The global mean surface temperature was 0.47 °C to 0.58 °C above the 1961–1990 annual average (14 °C) in the year 2005, making 2005 one of the warmest years since the year 1850. The years 1996–2005, with the exception of 1996 and 2000, are the warmest years on record. Based on analysis with different methodologies or reference periods, 2005 is marked as the warmest or second warmest year (uncertainties in these studies mainly arise from data gaps) (WMO, 2005).

In Switzerland, temperatures in the year 2005 were above average (1961–1990) in the lowlands on both sides of the Alps, but not in the high mountain areas. Precipitation amounts in 2005 were 12% below average with a significant precipitation deficit on the southern side of the Alps, where in some parts the lowest amounts since 1901 were recorded. Inspite of these relatively dry conditions, the most prominent event in 2005 was the devastating flooding in late August (MeteoSwiss, 2005).

Snow
Large amounts of precipitation fell on the Alpine South slope in October and November 2004 and the snow line was mostly between 2500 and 3000 m a.s.l. By mid-December snow thickness at high altitudes were no greater than lower down, which is unusual. By the end of December snow depths were average in most regions except the Grisons, where they were significantly lower than average. The next months were characterised by very little snowfall and stormy winds, which caused intense snow redistribution. The snow cover was very thin, even in high alpine locations. In mid-March there was a strong increase in air temperature and the 0 °C isotherm rose towards 3000 m a.s.l. The

snow cover immediately began to melt and at the end of March snow depths were below average in all regions.

Summer temperatures May–September 2005
Several periods between mid March and June were unusually warm (MeteoSwiss, 2005). Many meteorological stations already reported temperatures above 30 °C in May, which is exceptional. After a short break at the beginning of June, the warm weather continued until the beginning of July, when a remarkable temperature drop occurred. The summery weather returned briefly at the end of July, followed by a cool and rainy August with the extreme precipitation event from August 18–23. Late August and early September were very sunny with temperatures often around 30 °C. Then a remarkable temperature fall was triggered by a cold front marking the beginning of autumn.

2.2 Weather and Climate in 2005/2006

Both the weather and the climate data are based on the reports by the Federal Office of Meteorology and Climatology (MeteoSwiss, 2005, 2006). The snow data originate from SLF.

Weather and climate conditions in the hydrological year 2005/2006
According to WMO (2006) and the analyses made by leading climate centres the global mean surface temperature in 2006 was 0.42 °C to 0.54 °C above the 1961–1990 annual average, making 2006 the sixth warmest year on record. December 2006 was the warmest December since global surface records were instituted in 1861. Since the beginning of the 20th century, the global mean surface temperature has risen ca. 0.7 °C. However, this increase has not been continuous; since 1976, the global average temperature has risen sharply, at currently ca. 0.18 °C per decade.

In Switzerland, the year 2006 was the fifth warmest since 1864 with 1.2–1.6 °C warmer temperatures than average (MeteoSwiss, 2006). Only the years 1994, 2000, 2002, and 2003 were warmer. The first three months were characterized by below-average temperatures. This was then compensated by warm summery weather with above-average temperatures until the end of autumn, except for a cool and wet August. Precipitation fell in average amounts on the northern side of the Alps and in the Lower Valais. In the rest of Valais, Grisons, and Ticino rain fall was below average amounts.

Snow
The period September to November 2005 was very dry and warm with little snowfall, even at high altitudes. In mid-November snow fell to low altitudes and was unevenly distributed due to strong winds. The Jura and the western Pre-Alps were well endowed with snow at the beginning of December. Snow depths increased significantly in the West and North in the course of December 2005 and January 2006. On the southern slope of the Alps heavy snow falls occurred at the end of January. In January the snow depths on the Alpine North slope were mostly above average, with the exception of Valais, Tessin and Grisons where snow depths were average or just below. Intense snow falls occurred around mid-February, with around 200 cm of new snow in the lower Valais

Table 2.1: Key climatic features from the «Monthly weather reports of MeteoSwiss» (Meteo Swiss, 2004, 2005).

2004	
October	Mild with Foehn wind in the Alps. Otherwise wet and very cloudy in the South.
November	Little prec. in the North, mild in the South, strong prec. at the start of the month.
December	Sunny and mild in the mountains, temperature inversion fog in the North – mixed weather from mid-December onwards.
Year overall	Warmer than normal and changeable – hailstorm on the Plateau.
2005	
January	Sunny, spring weather, very wintery at the end, hardly any precip. in the South.
February	Wintery in the North during the second half of the month, very dry in the South.
March	Very cold start, very mild from mid-March onwards and little precipitation.
April	Mild with exceptional snowfall in the West.
May	Changeable, sunshine in the South – summery conditions at the end.
June	Extremely warm, very sunny, dry in many places – Summer from mid-June onwards.
July	Very warm and dry in the South. Changeable in the North – local thunderstorms.
August	Unstable, wet in the Alps with little sunshine – large storm and flood catastrophe.
September	Warm and dry in most areas.
Year overall	Warm in the lowlands, extremely dry in the South. Extreme precipitation in August.

Table 2.2: Key climatic features from the «Monthly weather reports of MeteoSwiss» (Meteo Swiss, 2005, 2006).

2005	
October	Sunny in the North and the mountains, dry in the south. Extremely mild at the end.
November	Very little precipitation – mild in the first half of the month, then onset of winter.
December	Cold mainly in the mountains – snow, freezing rain and thaw over the New Year.
Year overall	Warm in the lowlands, very dry in the South. Extreme precipitation in August.
2006	
January	Sunny, cold and dry. Extreme snowfall in the South.
February	Colder than normal, little sunshine and precipitation in the North.
March	Cold and wet, dry in the South - strong snowfall in the North.
April	Mild, unstable weather – wet in the North, dry in the South.
May	Warmer than normal – wet in the North, dry in the South.
June	Cold in the North first, then very warm and dry all over – a few hailstorms.
July	Hottest July – partly very dry, particularly sunny in the East.
August	Wet and unusually cold and cloudy in the North.
September	In part the warmest September - locally extreme rainfall in mid-September.
Year overall	Sunny, extremely warm and in the North wet – hottest July and warmest autumn since measurement began.

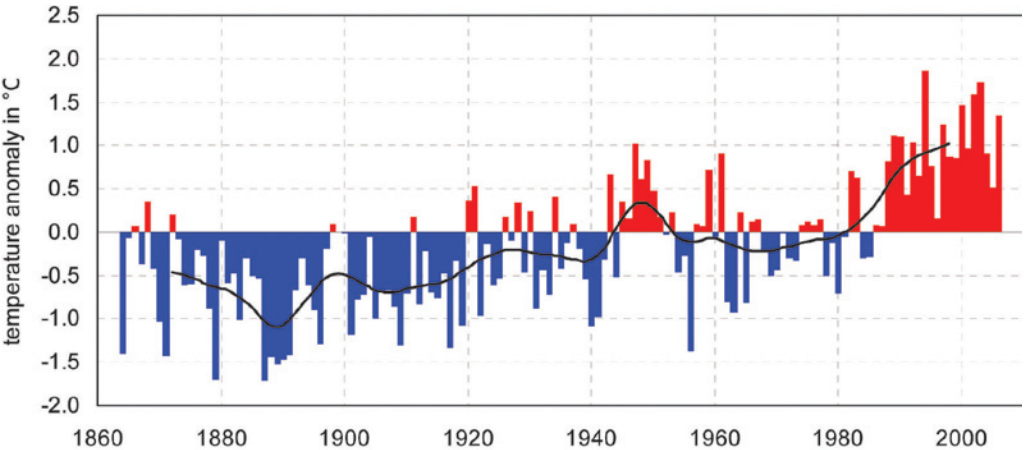

Figure 2.1: Mean annual temperatures in Switzerland 1864–2006. Blue indicates negative and red positive anomalies with respect to the period 1961–1990. Figure taken from MeteoSwiss (2006).

and 60–100 cm within 24h on the Alpine South slope. Record snow depths were attained at the beginning of March with another 150–200 cm of new snow in most areas of the Alpine North slope and northern Valais. Further snow fall occurred down to low altitudes at the beginning of April and spring conditions with warming air temperatures only started in mid-April.

Summer temperatures May–September 2006

Summer 2006 was very warm with an extremely hot July: in the lowlands north of the Alps and in most Alpine valleys the highest ever July temperatures were recorded (previous record in 1983) (MeteoSwiss, 2006). At the beginning of August, cool air masses dominated in Switzerland and in some areas the month of August was up to 2 °C cooler than average. However, the temperatures were similar to those typically recorded for August around 30 years ago. In September, the warmth returned and temperatures remained above average for the whole autumn, which was 2.5–3 °C warmer than normal. The previous record of the year 1987 was exeeded by 1 °C.

2.3 Climate Deviation from the Mean Value 1961–1990

The regional differences for the climatic elements precipitation and summer temperatures during the reporting period are illustrated in Figures 2.2 and 2.3. Analyses are based on data from the measurement networks ANETZ, NIME, and IMIS. Mean values 1961–1990 are based on the standard values determined within the projects KLIMA90 (Aschwanden et al., 1996) and NORM90 (Begert et al., 2003)

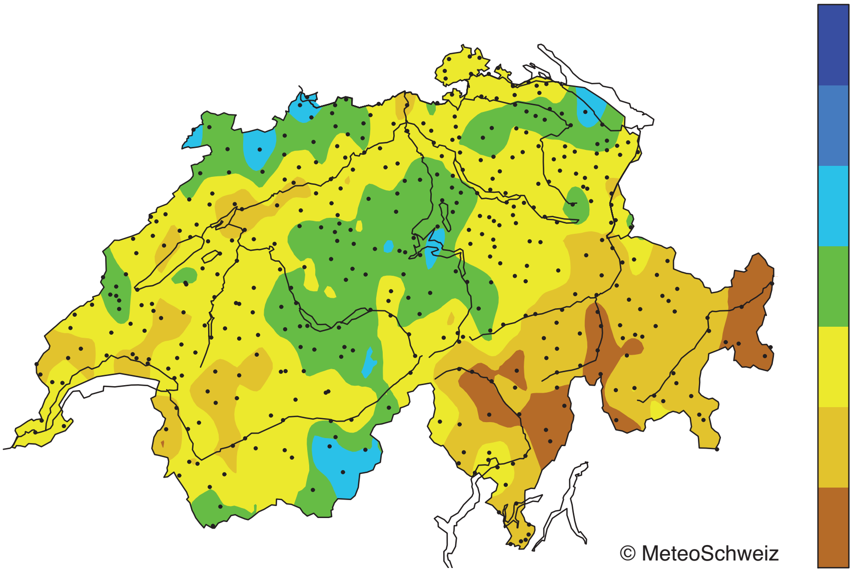

Figure 2.2a: Annual precipitation 2004/2005, deviation from the mean value 1961–1990 in percentage.

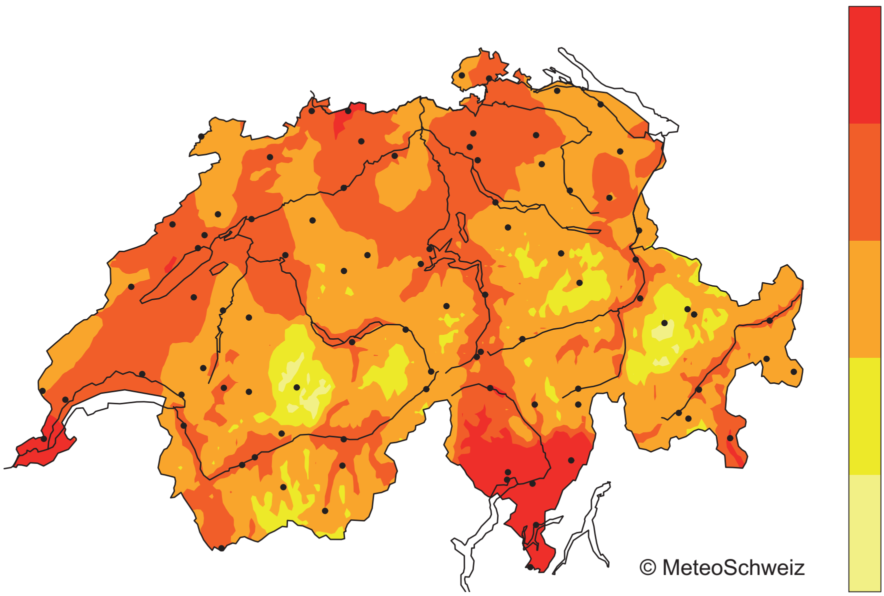

Figure 2.2b: Mean summer air temperatures 2005, deviation from the mean value 1961–1990 in degrees Celsius.

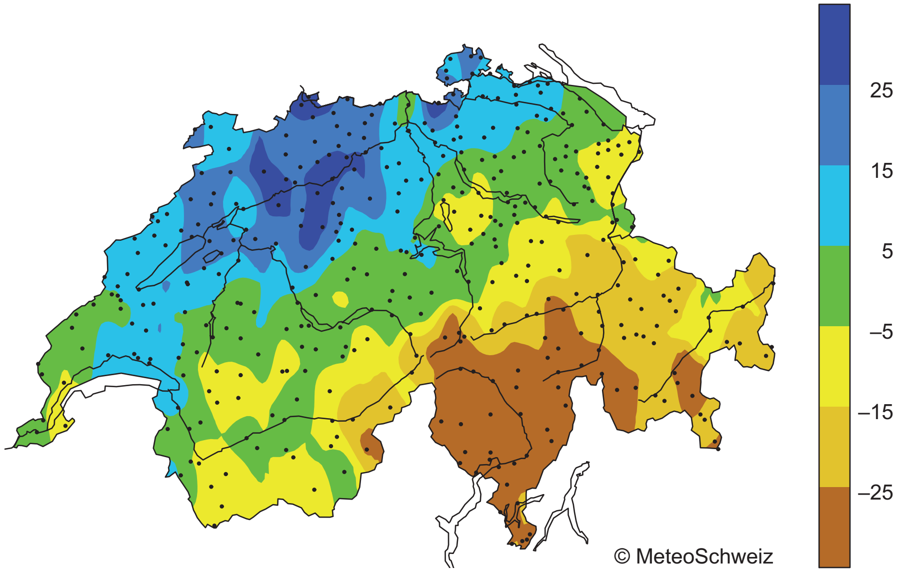

Figure 2.3a: Annual precipitation 2005/2006, deviation from the mean value 1961–1990 in percentage.

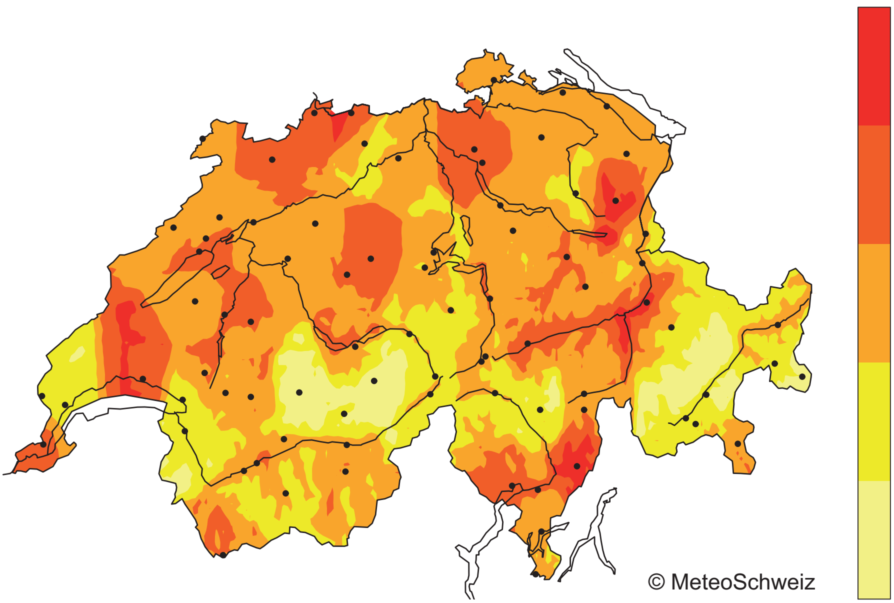

Figure 2.3b: Mean summer air temperatures 2006, deviation from the mean value 1961–1990 in degrees Celsius.

2.4 Duration of the Snow Cover

The date when the snow cover disappears can be determined based on continously recorded GST (i.e., the first day with temperatures >0 °C). Figure 2.4 shows the results for all PERMOS GST-sites (cf. Chapter 4).

The two years of the reporting period were characterized by snow melting earlier than average for the past decade at most sites. Depending on location, the snow cover melted 15–45 days earlier in 2005 than in 2004. This was particularly early at Schafberg in Upper Engadine. In the Valais and Bernese Alps, the snow disappeared close to the previous earliest date. In 2005, snow accumulation was low in winter and the weather was mild in spring and early summer. In 2006, a thicker snow cover resulted in snow melting 5–10 days later at lower elevations. The exceptionnally warm and sunny period from early June to end of July 2006 accelerated the snow melt at higher elevations and in areas of snow accumulation. However, at the PERMOS GST-sites the snow did not disappear earlier than in the previous year.

Photo 2: Meteo station at the borehole site Schilthorn in the Bernese Alps. Photo: H. Frey.

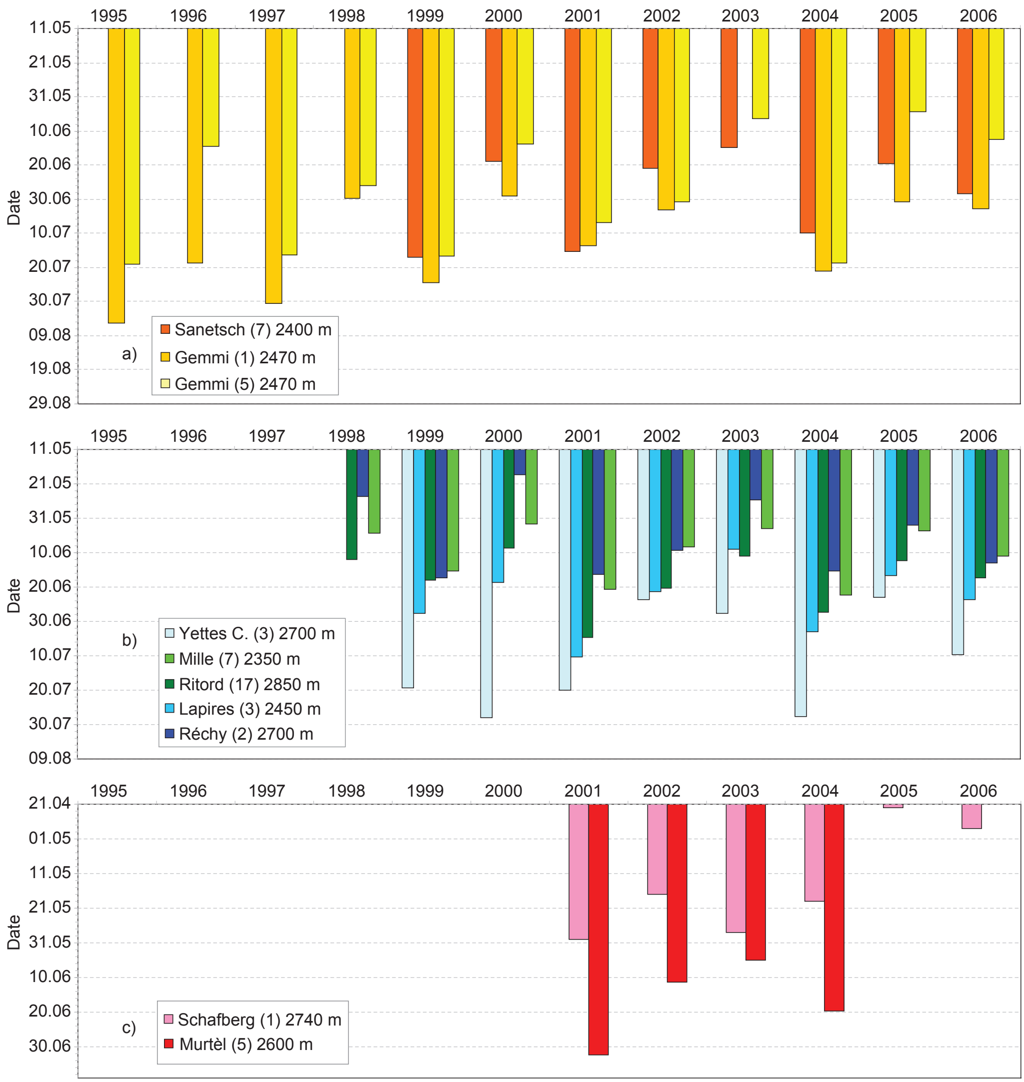

Figure 2.4: *Date of snow melt (1995–2006) at the GST-sites: a) Bernese Alps, b) Valais Alps, and c) Engadine. If data series from several data loggers are available, the mean value per site was calculated. Legend: Site (number of data loggers) mean elevation.*

3 Borehole Measurements

Permafrost temperatures are measured in boreholes at a number of sites in the conetxt of PERMOS. Based on these measurements the state and evolution of permafrost in the Swiss Alps is monitored. Further, the characteristics of the active layer in rock glaciers and scree slopes in the Swiss Alps are measured.

In this report for the measurement period 2004–2006, borehole temperature data from 22 boreholes at 11 PERMOS sites are presented (Table 3.1, Figures 3.1 and 3.2). In some cases the permafrost thickness can also be determined from the temperature measurements. Horizontal and vertical deformations were also measured in some boreholes. However, results are published individually.

In addition to the thermal monitoring in the boreholes, a geophysical monitoring network was initiated at several boreholes sites in 2005, based on a pilot study conducted on Schilthorn since 1999 (cf. Hauck, 2002, Hilbich et al., 2008, Glaciological Report Permafrost No. 4/5).

Figure 3.1: Locations of the PERMOS boreholes and ERT monitoring sites for the reporting period 2004–2006. Circles indicate sites with an ERT monitoring installed. Colors indicate different geographical regions.

3.1 Active Layer Thickness

The thickness of the active layer is defined by the depth of maximum penetration of the 0 °C isotherm into the ground in the course of the summer. Active layer thickness is a reflection of the local snow and atmospheric conditions reigning during the current year, as well as of the subsurface characteristics. Temperature and thickness of the active layer are typically influenced by the conditions of the previous year, and thus represent the conditions of the observed year.

Table 3.1: Borehole study sites. Data in PERMOS: L: Logger-measurements, M: Manual measurements; L. sensor: lowest sensor.

Borehole	Abbrev.	Data	ERT	Region (m)	Depth (m)	L.sensor (year)	Since
Jungfraujoch	N/95	L		Berner Oberland, BE	11.0	11.0	1995
Jungfraujoch	S/95	L		Berner Oberland, BE	10.0	10.0	1995
Schilthorn	51/98	L	x	Berner Oberland, BE	14.0	13.7	1998
Schilthorn	50/00	L	x	Berner Oberland, BE	101.0	100.0	2000
Schilthorn	52/00	L	x	Berner Oberland, BE	100.0	92.0	2000
Flüela	01/02	L		Flüelapass, GR	23.0	20.0	2002
Muot da Barba Peider	01/96	L		Upper Engadine, GR	18.0	17.5	1996
Muot da Barba Peider	02/96	L		Upper Engadine, GR	18.0	17.5	1996
Muragl	01/99	L		Upper Engadine, GR	70.2	69.7	1999
Muragl	02/99	L		Upper Engadine, GR	64.0	59.7	1999
Muragl	03/99	L		Upper Engadine, GR	72.0	69.6	1999
Muragl	04/99	L		Upper Engadine, GR	71.0	69.6	1999
Murtèl-Corvatsch	02/87	L	x	Upper Engadine, GR	62.0	58.0	1987
Murtèl-Corvatsch	01/00	—	x	Upper Engadine, GR	51.9	—	2000
Murtèl-Corvatsch	02/00	L	x	Upper Engadine, GR	63.2	62.0	2000
Schafberg-Pontresina	01/90	—		Upper Engadine, GR	67.0	—	1990
Schafberg-Pontresina	02/90	L		Upper Engadine, GR	37.0	25.2	1990
Arolla, Mt. Dolin	01/96	L		Val d'Herens, VS	10.0	5.5	1996
Arolla, Mt. Dolin	02/96	L		Val d'Herens, VS	10.0	5.5	1996
Gentianes	01/02	L		Bagnes-Nendaz, VS	20.0	20.0	2002
Lapires	01/98	L	x	Val de Nendaz, VS	19.6	19.6	1998
Stockhorn	60/00	L		Matter Valley, VS	100.0	98.3	2000
Stockhorn	61/00	L		Matter Valley, VS	31.0	20.0	2000
Tsaté	01/04	L		Val d'Herens, VS	20.0	19.5	2004

The active layer plays an important role in determining the thermal regime of the ground as well as influencing ground and infrastructure stability. The thickness of the active layer depends on site characteristics (e.g., elevation, aspect, soil characteristics, water supply). Sites with high ice contents at the top of the permafrost body tend to show less annual variation in active layer thickness (e.g., Murtèl-Corvatsch) than those with little ice content in the subsurface (e.g., Schilthorn). An overview of the active layer thicknesses for the reporting period at all PERMOS borehole sites is given in Table 3.2 and Figures 3.3a–f.

Active layer thickness was of particular interest in summer 2004, following the heat wave of summer 2003 (cf. Glaciological Report Permafrost, No. 4/5), during which active layers were exceptionally thick at some sites. Despite the early arrival of the snow cover in winter 2003/2004, active layer thicknesses in summer 2004 were similar to those preceding 2003 at all sites, with the exception of Stockhorn 60/00, where the active layer continued to deepen (5.4 m, as opposed to 2.9 m in 2002 and 4.3 m in 2003). In most boreholes, the near-surface layer of ground was therefore not subject to lasting thermal change during the 2003 heat wave, although the ice content at the permafrost table may well have been permanently modified. This could lead to subsidence of the ground surface and thinning of the permafrost body. The degree of subsidence can only be determined using methods such as photogrammetry or terrestrial surveys.

In summer 2005, Muragl 02/99, Lapires, and Stockhorn 61/00 again displayed a deepening of the active layer, reaching values similar to those measured in 2003. This may be a reflection of the warm spring and hot June in 2005. Interestingly, the active layer of Schilthorn 51/98 did not react to the higher temperatures in 2005, whereas a massive deepening of the active layer was registered here in 2003.

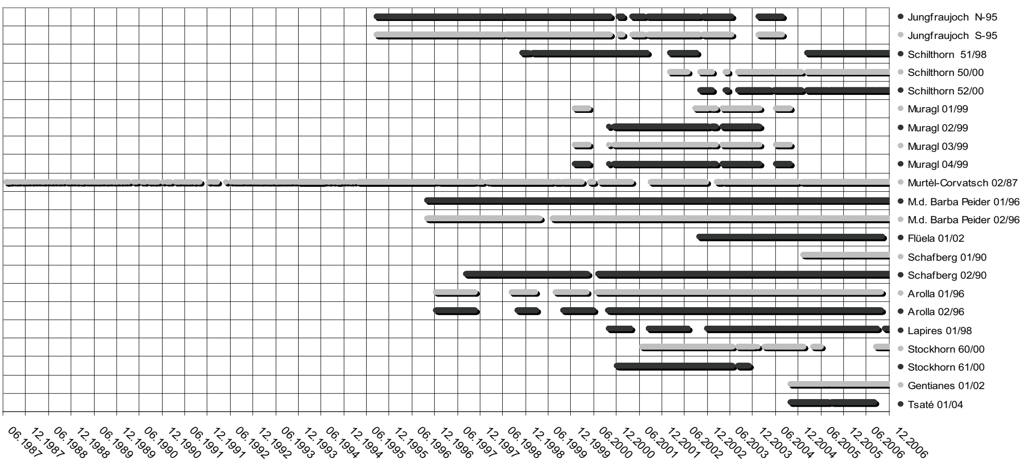

Figure 3.2: Available data for the PERMOS boreholes until 2006.

Table 3.2: Maximum thickness of the active layer (AL) and corresponding date for ther PERMOS boreholes in the years 2004, 2005, and 2006.

Borehole	2004 zmax (m)	2004 date	2005 zmax (m)	2005 date	2006 zmax (m)	2006 date
Jungfraujoch S/95	—	no data	—	no data	—-	no data
Jungfraujoch N/95	—	no AL rec.	—	no data	—-	no data
Schilthorn 51/98	4.81	05.10.2004	4.84	06.10.2005	4.84	06.10.2006
Schilthorn 50/00	4.75	24.09.2004	3.67	09.10.2005	3.74	07.10.2006
Schilthorn 52/00	2.87	01.10.2004	2.60	27.09.2005	1.28	26.09.2006
Flüela 01/02	2.90	13.09.2004	2.93	18.09.2005	2.94	25.09.2006
Muot da Barba Peider 01/96	0.98	09.09.2004	0.94	11.09.2005	0.97	03.08.2006
Muot da Barba Peider 02/96	2.08	21.09.2004	1.89	01.08.2005	1.91	01.08.2006
Muragl 01/96	—	no AL rec.	—	no data	—	no data
Muragl 02/99	6.95	07.09.2004	—	no data	—-	no data
Muragl 03/99	4.24	18.09.2004	—	no data	—-	no data
Muragl 04/99	—	no data	—	no data	—-	no data
Murtèl-Corvatsch 02/87	3.48	12.08.2004	3.47	02.08.2005	3.47	01.08.2006
Schafberg-Pontresina 01/90	—	no data	3.86	17.09.2005	3.87	22.09.2006
Schafberg-Pontresina 02/90	5.02	26.09.2004	4.97	17.09.2005	4.87	19.09.2006
Arolla 01/96	—	no AL rec.	—	no AL rec.	—	no data
Arolla 02/96	2.47	15.09.2004	2.48	08.09.2005	—	no data
Gentianes 01/02	1.39	10.10.2004	1.48	05.09.2005	1.38	04.10.2006
Lapires 01/98	4.55	10.2004	4.65	11.10.2005	—	no data
Stockhorn 60/00	5.41	28.09.2004	—	no data	4.76	29.08.2006
Stockhorn 61/00	3.92	27.10.2004	—	no data	—	no data
Tsaté 01/04	13.0	23.10.2004	6.47	22.10.2005	—	no data

Despite extremely high air temperatures in June and July 2006, further deepening of the active layer was only recorded in Muragl 02/99 (reaching a record 7 m). Active layer depths in all other boreholes remained stable, with the exception of Schilthorn 52/00, where a significant reduction in active layer thickness (1.3 m as opposed to 2.6 m in 2005) was registered.

Several sites (Muragl 04/99, Flüela 01/02, Murtèl-Corvatsch 02/87, Arolla 01/96, and Gentianes 01/2002) have had more or less unchanging active layer thicknesses since measurement begin (even during the 2003 heat wave). This striking lack of variability is probably due to high ice contents at

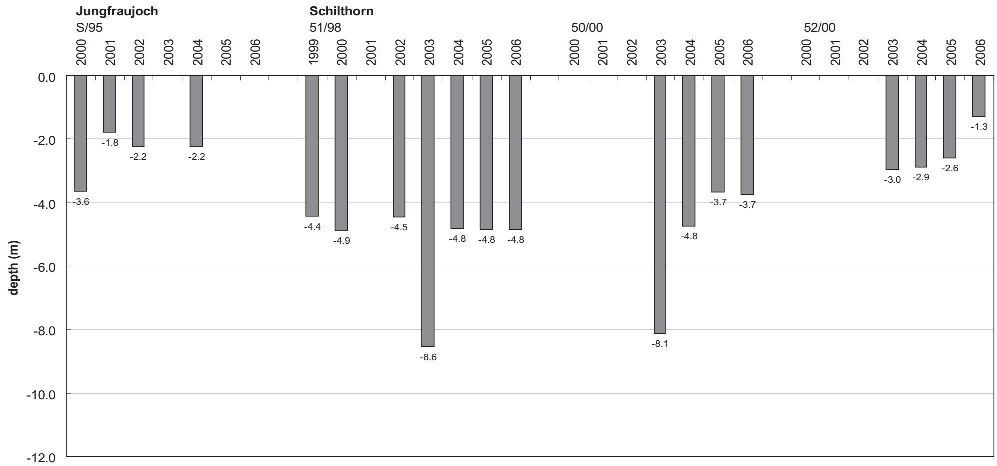

Figure 3.3a: Maximum active layer thickness for the boreholes in the Bernese Alps, until 2006.

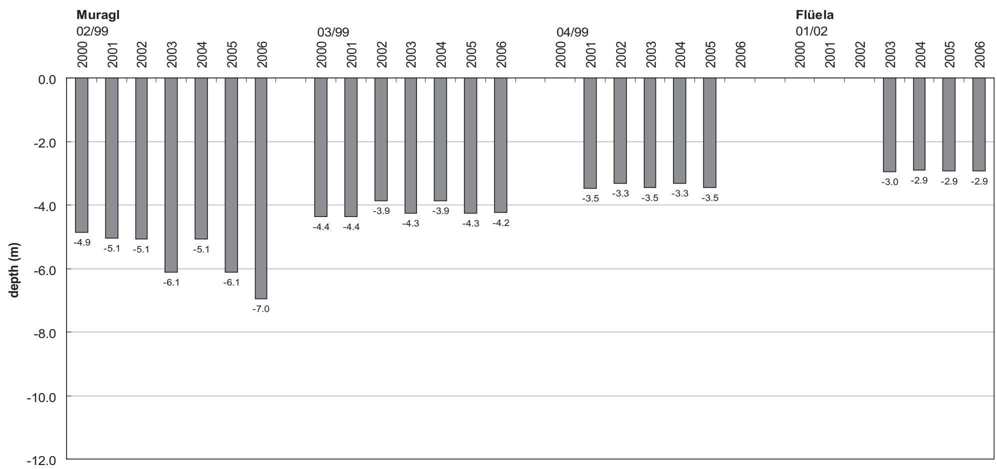

Figure 3.3b: Maximum active layer thickness for the boreholes Muragl 02/99, 03/99, 04/99, and Flüela 01/02 in Grisons, until 2006.

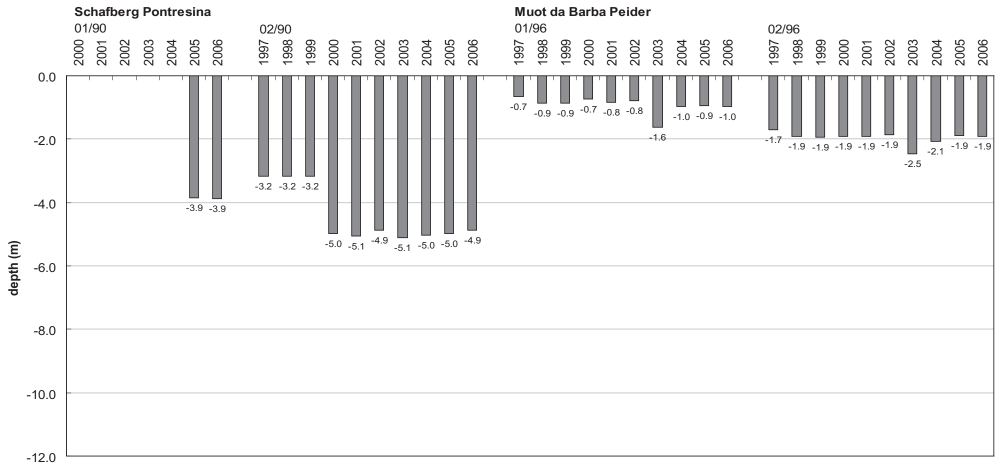

Figure 3.3c: *Maximum active layer thickness for the boreholes Schafberg Pontresina 01/90, 02/90, Muot da Barba Peider 01/96 and 02/96 in Grisons, until 2006.*

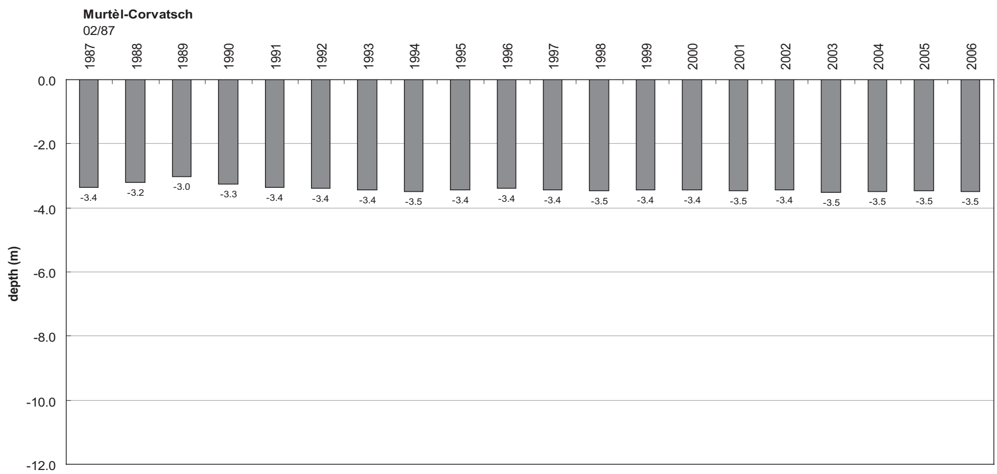

Figure 3.3d: *Maximum active layer thickness for the Murtèl-Corvatsch borehole 02/87, until 2006.*

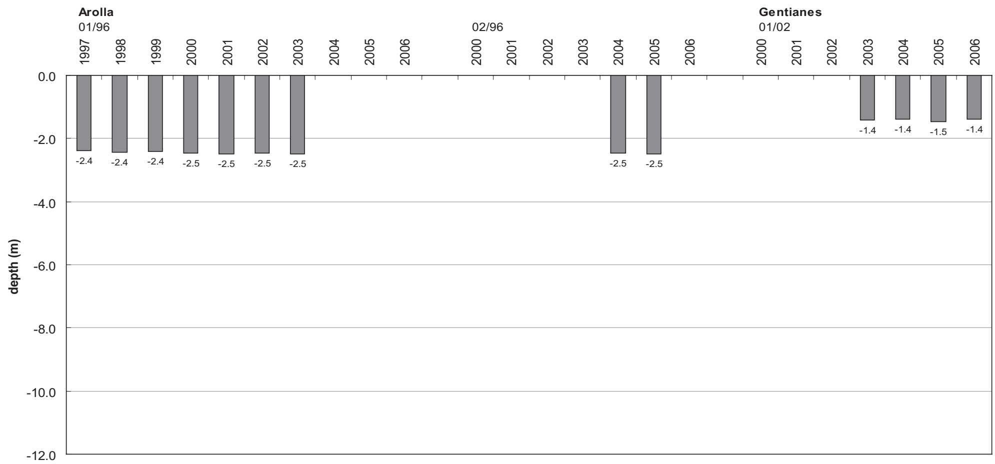

Figure 3.3e: *Maximum active layer thickness for the boreholes Arolla 01/96, 02/96, and Gentianes 01/02 in Valais, until 2006.*

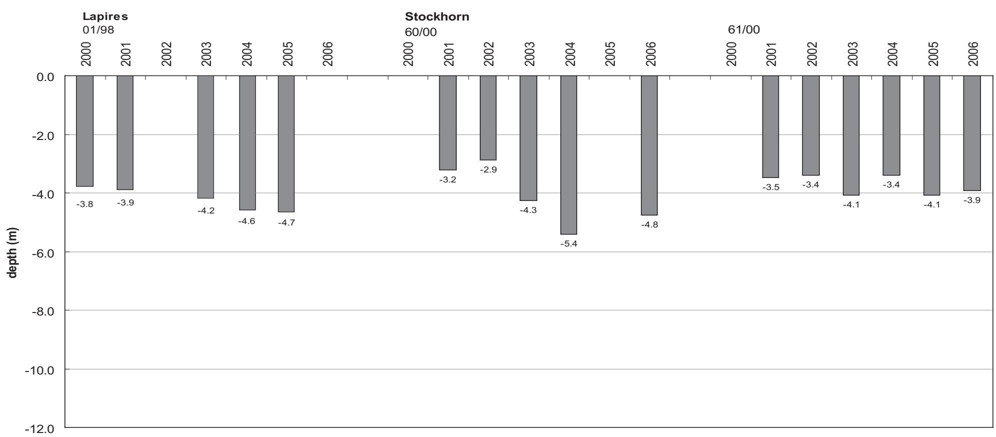

Figure 3.3f: *Maximum active layer thickness for the boreholes Lapires 01/98, Stockhorn 60/00, and 61/00 in Valais, until 2006.*

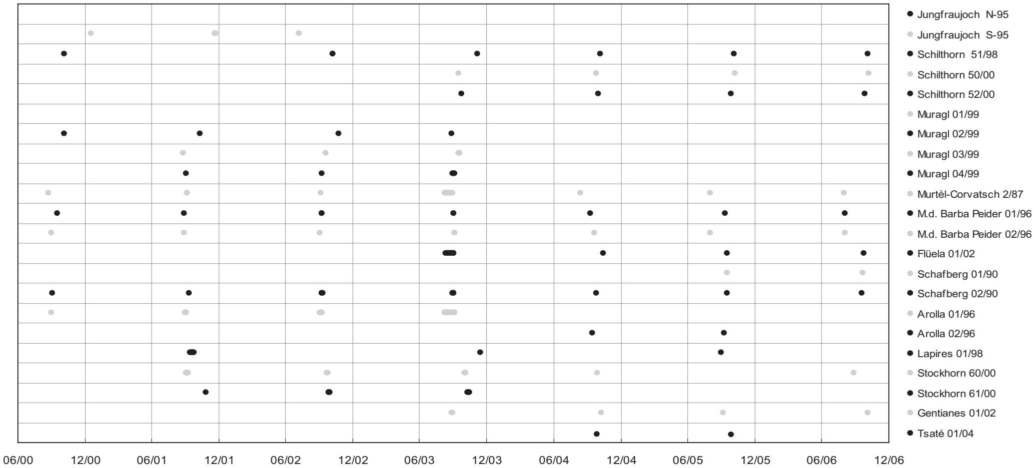

Figure 3.4: Date of maximum active layer thickness in the years 2000–2006.

the permafrost table and indicates that the energy requirements for significant active layer thickening are not met.

The date of maximum active layer thickness is site-specific and varied between early September (Muragl 02/99) and late October (Stockhorn 61/00) in 2004 and between early August (Muot da Barba Peider 02/96) and early October (Schilthorn 50/00) in summer 2005 (Figure 3.4). In summer 2006 maximum active layer thickness was attained in early August for the Engadin boreholes Murtèl-Corvatsch 02/87 and Muot da Barba Peider 01/96 and 02/96, whereas it was early October for the Schilthorn boreholes.

3.2 Permafrost Temperatures

As near-surface ground temperatures in mountains are strongly influenced by factors such as topography, ground cover, and snow cover distribution, borehole temperatures at greater depths are used for comparison between sites and to allow the observation of seasonal temperature variations. At ca. 10 m depth noise induced by external diurnal variations and local surface characteristics can be more or less disregarded, due to the damping effect of the ground, which causes a thermal lag of around 6 months here.

The temperatures at ca. 10 m depth (Figure 3.5) in 2004, 2005, and 2006 reveal the importance of both, air temperatures and the timing of the snow cover as regulators of ground temperatures at

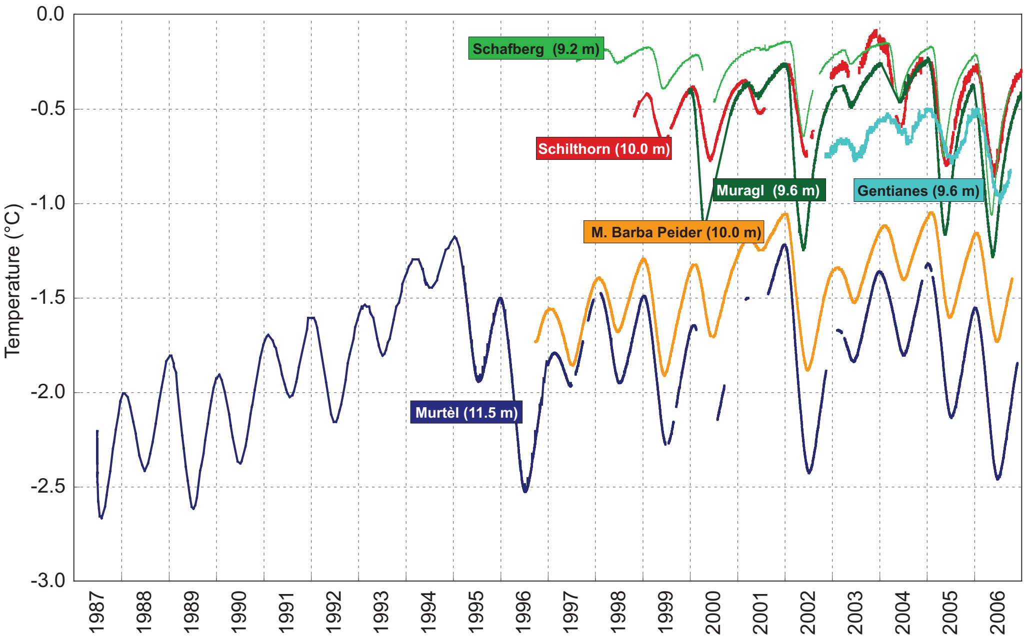

Figure 3.5: The longest time series at Murtèl-Corvatsch allows to relate the reporting period to the past 15 years.

the regional to national scale. The effects of heat stored in the ground during summer 2003 and the insulating effect of the early arrival of snow at the beginning of winter 2003–2004 are reflected in high thermal maxima and minima in 2004. The maxima were even higher at the beginning of 2005 (possibly reflecting the hot August and October 2004), reaching levels similar to those attained in early 2002 (cf. Glaciological Report Permafrost, No. 2/3). From this point onwards, a lowering of both, minima and maxima occurred, likely induced by a very thin snow cover in most regions during winter 2004–2005, which allowed the ground to cool in the winter months, and by the late arrival of snow in winter 2005–2006. These effects can be seen at all sites, regardless of altitude and region.

In contrast, absolute differences between individual boreholes (Figures 3.6 to 3.8) reflect the additional influence of individual local parameters such as mean annual air temperature, ground surface and subsurface characteristics, ice content or radiation. Whereas the sites Schafberg, Schilthorn, and Muragl have had similar temperatures at 10 m depth since measurement begin, Gentianes is slightly colder (but with little annual variability) and Muot da Barba Peider and Murtèl-Corvatsch are significantly colder. Muragl and Murtèl-Corvatsch, both rock glaciers with very coarse blocky surfaces, tend to display more intense and higher rates of seasonal cooling.

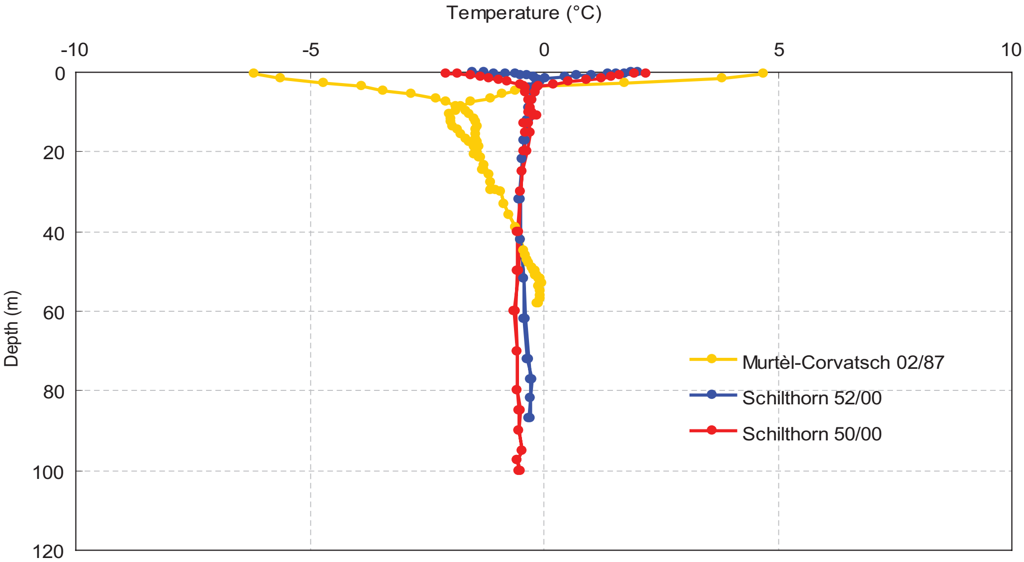

Figure 3.6a: Monthly mean temperatures for the boreholes Murtèl-Corvatsch 02/87, Schilthorn 52/00, and Schilthorn 50/00 in March and September 2005.

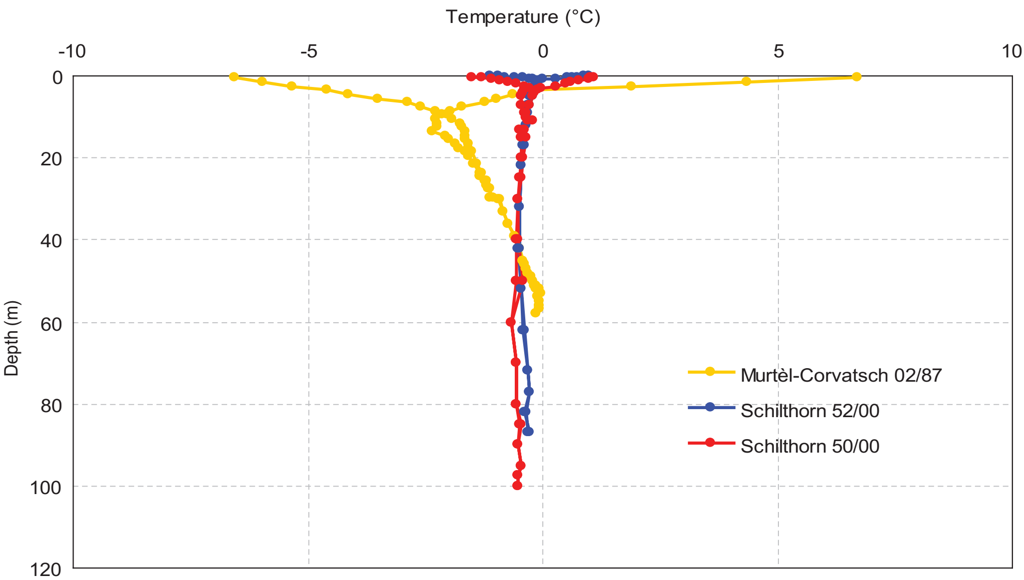

Figure 3.6b: Monthly mean temperatures for the boreholes Murtèl-Corvatsch 02/87, Schilthorn 52/00, and Schilthorn 50/00 in March and September 2006.

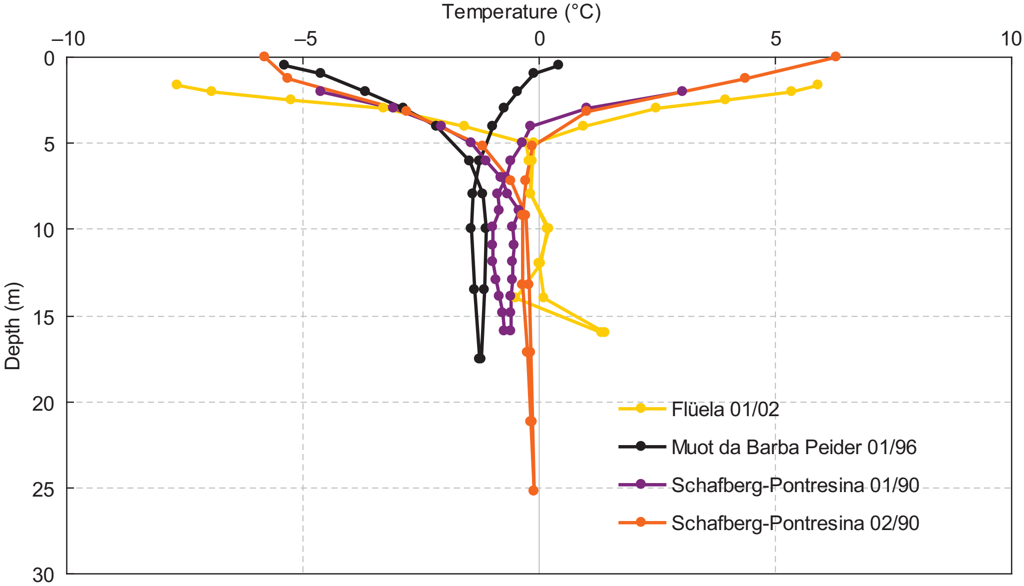

Figure 3.7a: *Monthly mean temperatures for Flüela 01/02, M.d. Barba Peider 01/96, Schafberg-Pontresina 01/90, and Schafberg-Pontresina 02/90 in March and September 2005.*

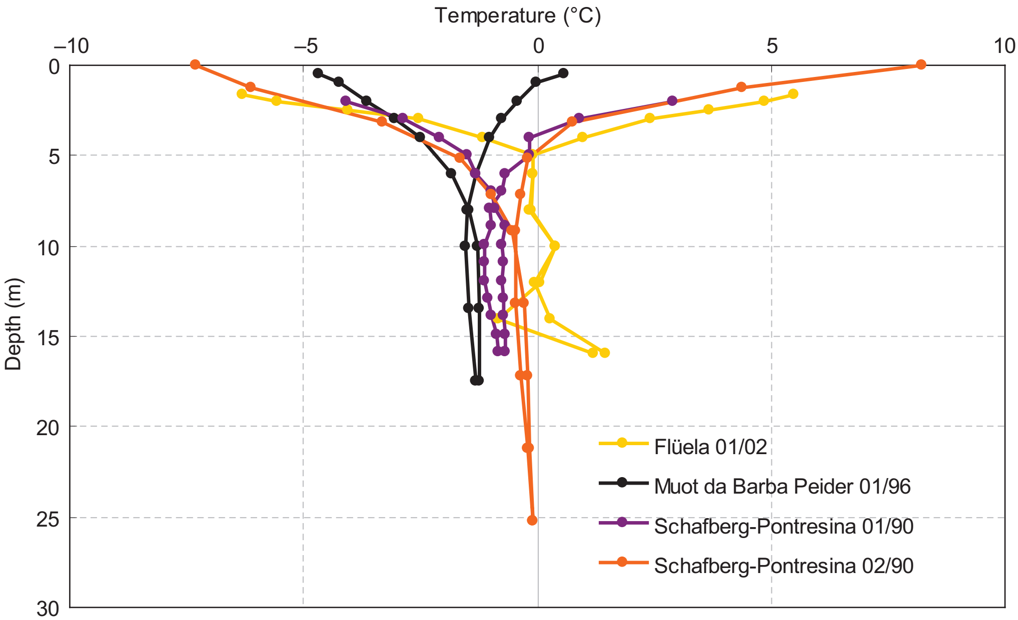

Figure 3.7b: *Monthly mean temperatures for Flüela 01/02, M.d. Barba Peider 01/96, Schafberg-Pontresina 01/90, and Schafberg-Pontresina 02/90 in March and September 2006.*

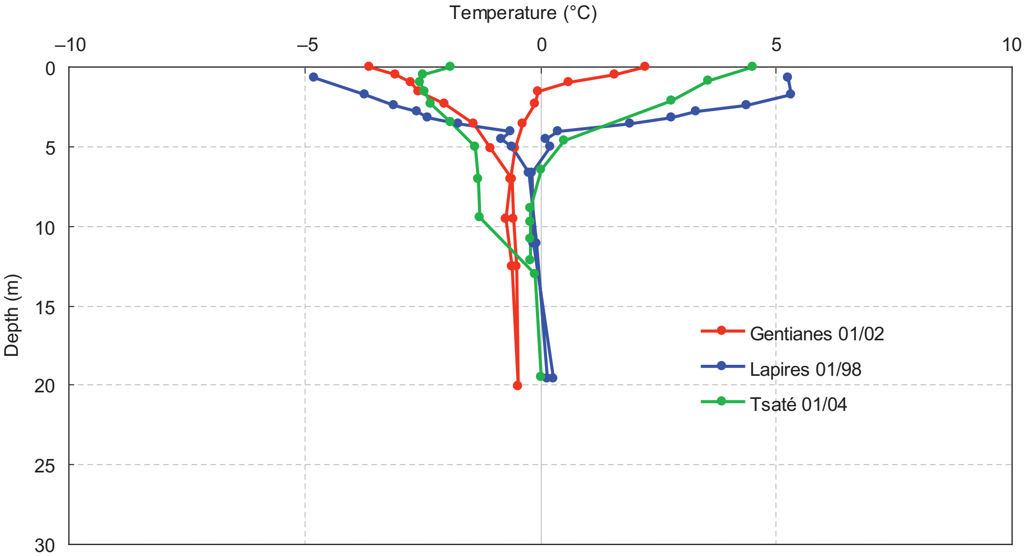

Figure 3.8a: *Monthly mean temperatures for the boreholes Gentianes 01/02, Lapires 1/98, and Tsaté 01/04 in March and September 2005.*

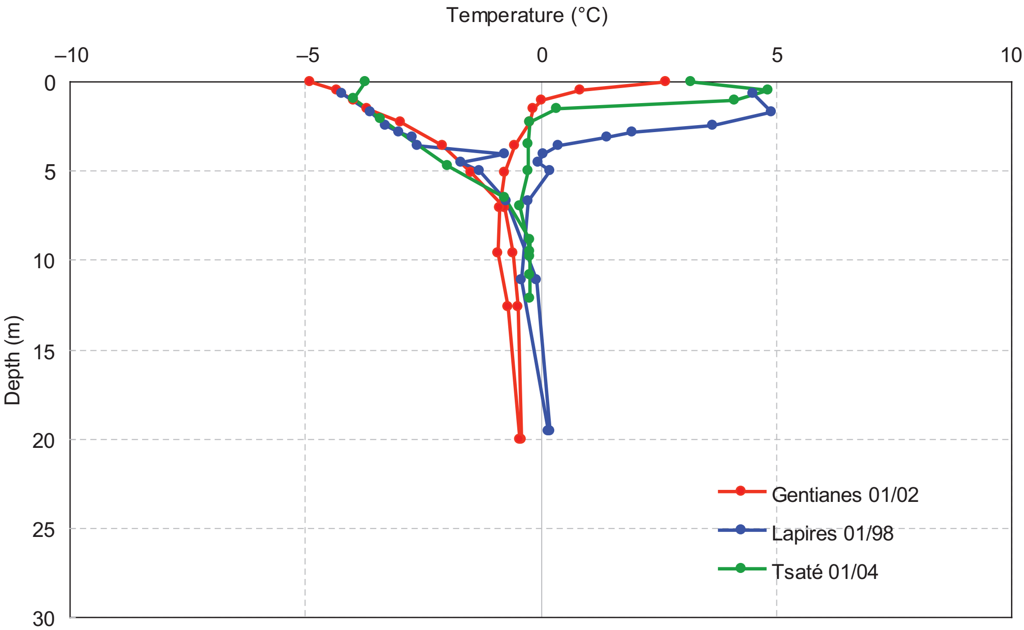

Figure 3.8b: *Monthly mean temperatures for the boreholes Gentianes 01/02, Lapires 01/98, and Tsaté 01/04 in March and September 2006 (Tsaté: August 2008).*

3.3 ERT Monitoring Network

3.3.1 Introduction

In addition to temperature, ice content is one of the most critical parameters for the evaluation of the impact of global warming on permafrost evolution. Direct observations of ice content are scarce and difficult to obtain.

The PERMOS ERT monitoring network was initiated based on the necessity of (a) characterization of the physical properties of the various permafrost occurrences (i.e., ice content, unfrozen water content), (b) spatially differentiated long-term monitoring of freeze and thaw processes in terms of changes in ice/unfrozen water content in addition to the observed temperature in boreholes, (c) input and validation data (e.g., vertical structure, porosity, ice/water content) for subsurface modelling of the permafrost evolution, and (d) analysis of causes of instability phenomena (e.g., rock glacier acceleration, degradation phenomena).

From the large variety of geophysical methods Electrical Resistivity Tomography (ERT) provides a remarkable potential for permafrost monitoring, as measured electrical resistivity depends on both, temperature and unfrozen water content. The dependence is most pronounced for temperatures below the freezing point, indicating the close relation between the fraction of pore space filled

Photo 3: Rock glacier Murtèl-Corvatsch and cable car station Murtèl in the Upper Engadine. Photo: J.Noetzli.

with unfrozen water and electric conduction. During freezing, measured electrical resistivity will rise strongly as unfrozen water content within a substrate decreases. Thus the electrical resistivity is sensitive to phase changes between water and ice (which are also influenced by other effects, such as impurities) and therefore is directly associated with the ice content of the subsurface material (Hilbich et al., 2008).

Under the assumption that general conditions (lithology, pore space, electrode coupling, etc.) remain constant over several years of observation, measured changes in resistivity can be attributed to changes in the unfrozen water content. In the absence of changes in water contents as a result of rain or snowmelt, these resistivity changes can be related to freezing or thawing processes and subsurface temperature changes, respectively. In the rather dry high mountain regions of the European Alps, where most precipitation occurs as snow, temporal changes in unfrozen water content due to rain or snowmelt can usually be distinguished from freezing and thawing processes because of their seasonal character, with a peak in late spring and early summer and a relatively rapid drainage of liquid water due to the absence of impemeable layers in the shallow subsurface.

As results of ERT monitoring can be directly linked to changes in frozen and unfrozen water content of the subsurface and therefore to permafrost evolution, the method provides complementary information to temperature measurements. ERT results from the pilot study on Schilthorn, including the exceptional hot summer 2003 with the remarkable increase in the depth of the active layer from typically approximately 5 m to 9 m (cf. Glaciological Report Permafrost, No. 4/5), indicated substantial degradation of ground ice and showed the potential of a combined thermal and ERT monitoring approach compared to thermal monitoring only (Hilbich et al., 2008).

3.4.2 Installation and Monitoring Strategy

Establishment of the ERT monitoring network includes (Figure 3.9): (1) installation, (2) data acquisition, and (3) data processing. Data acquisition may comprise manual measurements of all necessary quadrupoles of a certain electrode configuration (e.g., Wenner) using any kind of resistivity meter. Alternatively, an adapter linking the manual switchbox to a multi-electrode resistivity instrument can be used to facilitate measurements. For the latter, the time for a complete survey is less than one hour. Data processing includes the analysis of measured apparent resistivities for quality assessment (cf. Hilbich et al., 2008) and data inversion to determine the specific resistivity in space and time. Hereby, some constraints concerning investigation depth and accuracy of the results have to be taken into account (Hilbich et al., 2009).

3.4.3 ERT Monitoring Network

ERT monitoring sites (Figure 3.1, Table 3.3) have been chosen to represent different permafrost landforms, different climatic regions in the Swiss Alps, and with respect to the availability of deep boreholes (≥20 m). The landforms include the north-facing rock slope of Schilthorn (Bernese Alps), the rock plateau Stockhorn (Valais), the talus slope Lapires (Valais), and the active rock glacier Murtèl-Corvatsch (Upper Engadine). All ERT profiles are close to a PERMOS borehole to enable cali-

Table 3.3: Details of the sites of the ERT monitoring network.

Site	Installed	Scale (no. of electrodes, spacing)	No. of data sets	Substrate
Schilthorn	08/1999	30 electrodes, 2 m	>100	fine debris
Schilthorn summit	08/2006	47 electrodes, 4 m	12	fine debris, bedrock
Murtèl	08/2005	48 electrodes, 5 m	10	rock glacier
Lapires	08/2006	48 electrodes, 4 m	17	talus slope
Stockhorn	08/2005	48 electrodes, 2 m	11	debris on bedrock

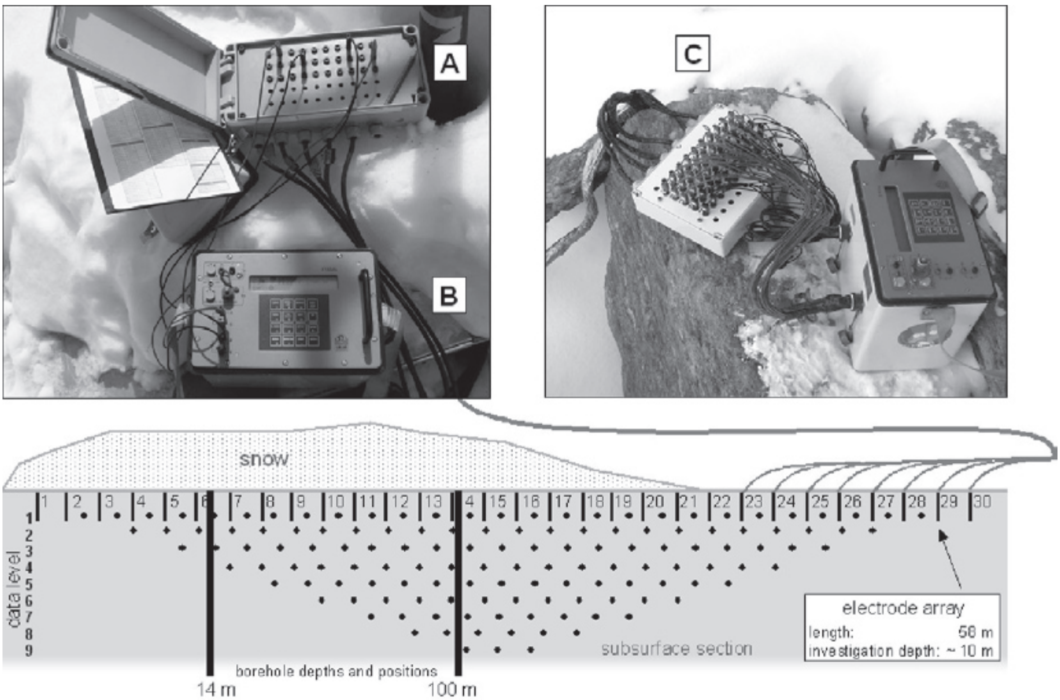

Figure 3.9: Working principle of the ERT monitoring system operating at Schilthorn: Electrodes are buried in the ground (1 m deep) and are connected to a manual switchbox (marked A) by buried cables. ERT measurement can be performed by connecting any resistivity meter (marked B) to the switchbox with four pin plugs and switching the pin plugs for the quadrupoles of a specific configuration. Optionally, a matching adaptor (marked C) for a defined multi-electrode resistivity meter can be used for automatic measurement of the entire configuration (taken from Hilbich et al., 2008).

bration of the indirect geophysical measurements with direct observations of the subsurface material composition as made during drilling and subsurface temperature records of the boreholes.

In addition to the already existing cross profile along the boreholes at Schilthorn, a 164 m long profile across the (E-W directed) crest was installed in 2006. This profile does not only have a much larger penetration depth (25 m instead of the 10 m of the existing profile), but includes both the north and south exposed slopes of the Schilthorn summit, thus yielding more information on the influence of topography on the subsurface thermal field. Similar to Schilthorn, the profile at Stockhorn uses the geometry of the summit (rock plateau) to cover north and south exposed slopes, increasing accuracy due to the advantageous geometry for tomographic inversion. The profiles at the talus slope Lapires and rock glacier Murtèl-Corvatsch cover permafrost morphologies with additional effects caused by air ventilation and convection through the coarse blocks.

3.3.4 Results 2004–2006 and Discussion

Schilthorn

As discussed in detail in Hauck (2002) and Hilbich et al. (2008) the overall resistivity values are very low at Schilthorn, due to the presence of fine-grained material and temperatures near the freezing point (> –0.7 °C).

Comparing the annual measurements at the end of the summer (end of August–September) (Fig. 3.10) significant resistivity changes can be observed. Especially in the left (eastern) part of the profile, where the borehole 51/98 is located, anomalously low resistivity values are detected in 2003, which persist in 2004 and only slowly increase until 2006, when the original values of 1999 are reached again. While the comparatively minor changes in resistivity between the summer of 1999 to 2000 and 1999 to 2002 seem to reflect the inter-annual variability of permafrost dynamics due to atmospheric forcing, the hot summer of 2003 obviously had an effect on the local permafrost regime that was sustained for more than 1 year. The significant active layer increase from 1999–2002 to 2003 is also clearly visible in the ERT tomograms.

While the temperature regime seems to have recovered in 2005 from the 2003 heat anomaly, the resistivity values have not. Although resistivities increased again in 2005, they did not exceed 1700 Ωm in those parts where resistivity had reached 2500 Ωm in the years before 2003 (Figure 3.10). This difference is small compared to seasonal variations, but large in an inter-annual context. Subzero temperatures were nearly identical before 2003 and after 2004 and can not explain the differences in resistivity. Hence a substantial loss of ground ice is assumed during summer 2003, which has not, so far, entirely recovered (Hilbich et al., 2008).

Lapires

In Figure 3.11 the results for August and December 2006 are shown in comparison to a previous measurement in 1999 by Delaloye (2004). Even taking into account the fact that discrepancies between the two measurements may be due to small differences in profile location and/or measurement configuration, the strong increase in resistivity of the high-resistive central anomaly between the two years is prominent. From the borehole results this anomaly can be clearly attributed to a

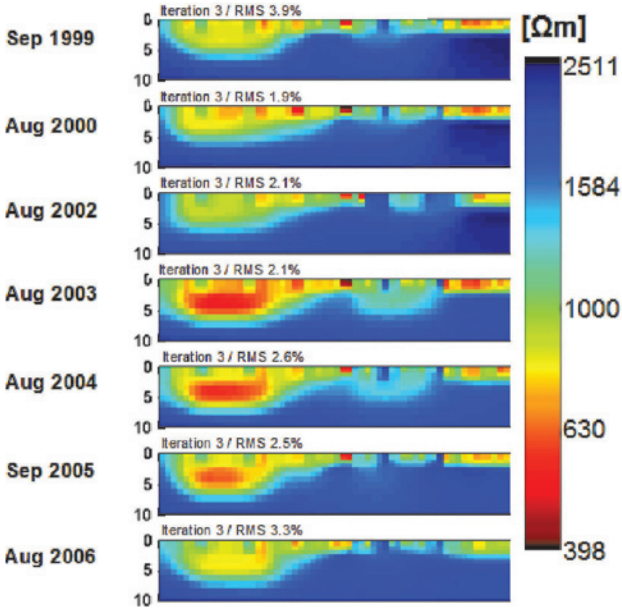

Figure 3.10:
ERT monitoring results for end-of-summer measurements at Schilthorn.

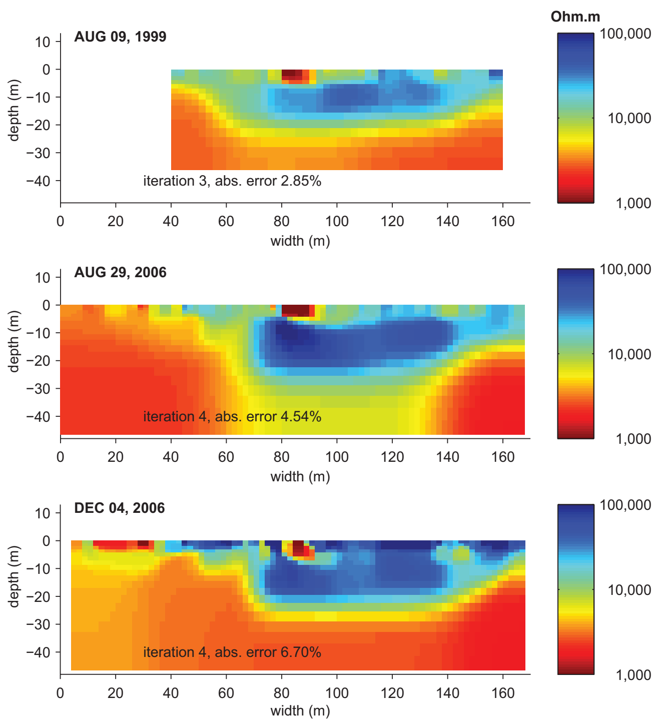

Figure 3.11:
ERT monitoring results for August and December 2006 at Lapires in comparison to a previous measurement in August 1999 by Delaloye (2004).

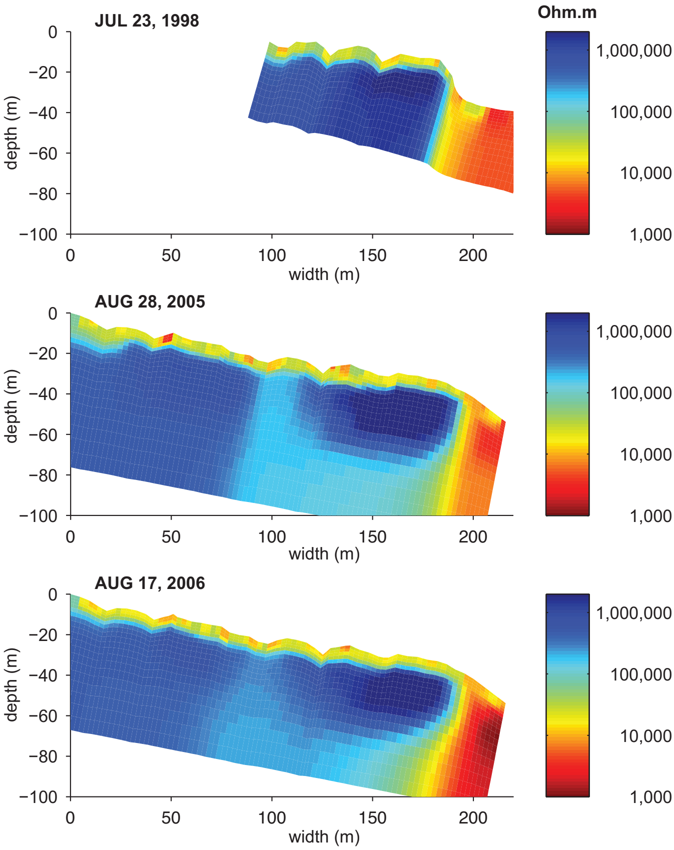

Figure 3.12: ERT monitoring results for August 2005 and 2006 at rock glacier Murtèl-Corvatsch in comparison to a previous measurement in July 1998 shown in Hauck and Vonder Mühll (2003).

ground ice occurrence. Whether the higher resistivity in 2006 is connected to an increased air circulation in the talus slope is subject to further investigation.

Comparing the December and August 2006 measurements, the development of a freezing front from the surface in December is clearly seen. Note also that the resistivity of the ice body is also slightly decreased in the December measurements, possibly indicating a relation with the reversed air circulation.

Murtèl-Corvatsch

Similar to the Lapires site, the 2005–2006 results for rock glacier Murtèl-Corvatsch are shown in comparison with a previous ERT measurement from summer 1998 (Figure 3.12). The 1998 profile was much shorter with a correspondingly much smaller penetration depth. Clearly, due to the geometry and the reduced penetration depth the 1998 measurement failed to detect the decreasing resistivity values below the ice core located at around 150 m on the later profile, or the zone with reduced resistivities around 100 m. The latter zone with reduced resistivity values seems to indicate a remarkable feature with potentially larger annual changes than seen from the borehole. However, resistivity changes near or below a high-resistive anomaly have to be carefully analysed in ERT tomograms as inversion artefacts may falsely indicate significant temporal changes at depth, where only changes in the active layer were present (see Hilbich et al., 2009). Nevertheless, further analysis showed that the zone with lower resistivities around 100 m distance is indeed a region where potential permafrost degradation may take place on an otherwise slowly changing rock glacier.

3.4 Conclusions Boreholes

Conclusions Borehole Temperatures
In the first half of the reporting period, active layer depths and ground temperatures at 10 m depth were still influenced by the combined effects of the 2003 summer heat wave and an early, abundant snowfall in October 2003. From the beginning of 2005 onwards, a lowering of annual temperature maxima and minima was registered at depth. By 2006, active layer thicknesses at most sites were back to their pre-2003 values, except at one site (Muragl). It should be noted that some subsidence might have occurred at the permafrost table as a result of the heat wave, leading to a thinning of the permafrost body in places.

Conclusions ERT
After the successful completion of the pilot study on Schilthorn, the first results from 2 years of ERT monitoring within PERMOS showed the suitability of the approach also for rock glaciers (Murtèl-Corvatsch) and talus slopes (Lapires). The overall repeatability and accuracy of the approach was good enough for 2-D analysis of resistivity changes in the context of permafrost evolution. As sufficient data are not yet available from the newly equipped monitoring stations, the results at Lapires and Murtèl were compared to previous measurements in 1999 and 1998.

Seasonal and annual changes could well be distinguished from small inter-annual «noise» and horizontally and vertically heterogeneous changes could be detected for the different years. The following years will show to what extent the new monitoring ERT time series will confirm the borehole temperature time series, and will contribute to a better understanding of the permafrost evolution at the borehole sites.

4 Surface Temperatures

The variation in surface and near-surface temperatures is a key parameter influencing the thermal regime of the subsurface and, thus, permafrost. The most important factors that determine near-surface temperatures are air temperature, solar irradiation, snow cover characteristics, and active-layer characteristics. Ground temperatures measured several meters deep in boreholes reflect the integrated and delayed signals of all these components.

Within PERMOS, surface temperatures are measured at locations with different topographic factors and varying surface and subsurface characteristics using appropriate techniques. That is, in

(a) loose sedimentary material (e.g., talus, moraine)
- mapping of the bottom temperature of snow cover (BTS) in late winter
- continuous recording of ground surface temperatures (GST), and in

(b) bedrock
- continuous recording of rock surface temperature (RST), both on gently inclined slopes and in near-vertical rock walls.

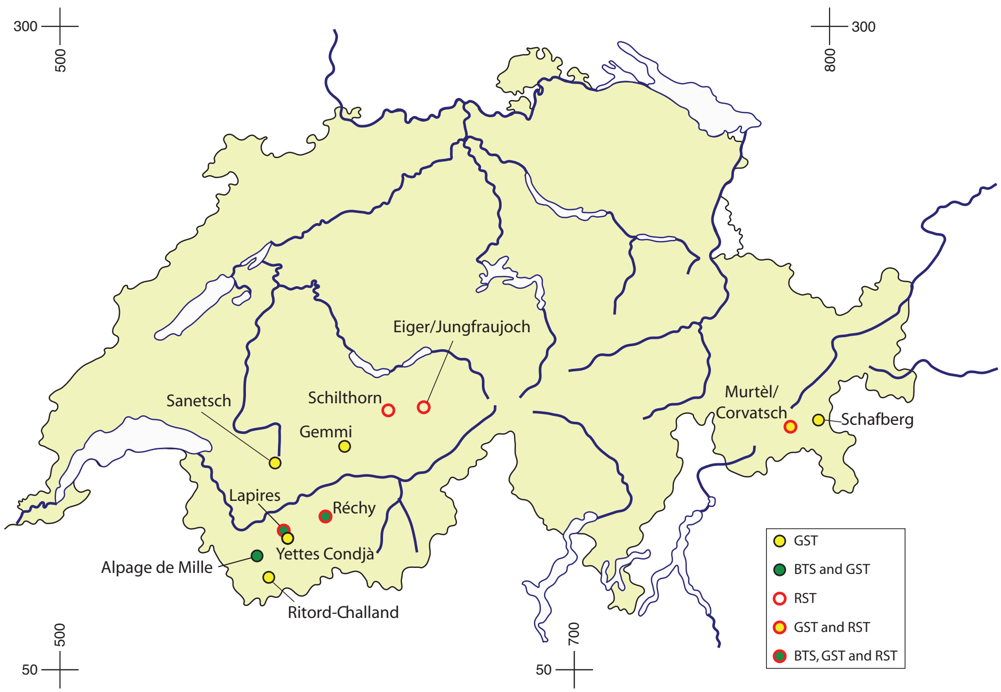

Figure 4.1: Locations of BTS-, GST- and RST-sites.

4.1 Surface Temperatures in Unconsolidated Sediments

4.1.1 Bottom Temperature of the Snow Cover (BTS)

BTS measurements were performed on 2 sites in 2005 (i.e., Lapires and Mille) and on only one site in 2006 (Mille) (Table 4.1). Both sites are located in the western Valais Alps (Figure 4.1). Mean values for BTS and snow depth are depicted in Figure 4.2. At Mille, the two years were the coldest since the beginning of the systematic measurements in 1996.

The snow cover was particularly thin in 2005 at the time of the BTS (early March). At Mille it reached the lowest value since 1996, and at Lapires since 2001. The snow depth in 2006 was equal to the mean value 1996–2006.

4.1.2 Ground Surface Temperatures (GST)

GST was measured in the reporting period 2004/2005 and 2005/2006 at 10 sites (Figure 4.2) instrumented with 7–39 single-channel temperature data loggers (Table 4.2). Most of the loggers are located on rockglaciers, talus slopes, and moraines with slope angles ranging from 0 to 40°. A relatively thick snow cover (i.e., 0.5 to more than 3 m) typically develops at these sites during winter, except for a few wind-exposed locations.

The main parameters observed are (a) the duration of the snow cover (cf. Chapter 2.4), which indicates how long the ground is protected from summer warming, (b) the Ground Freezing Index

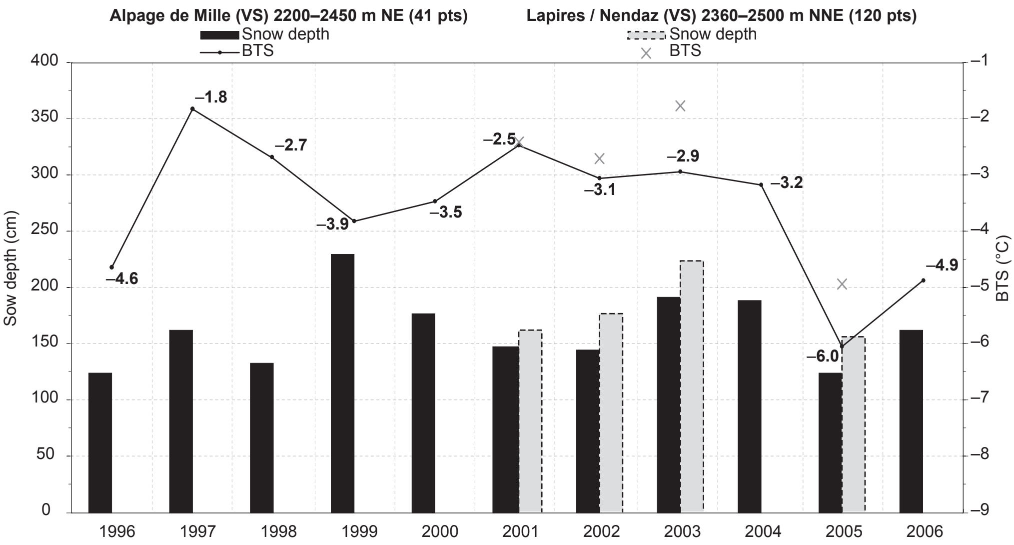

Figure 4.2: Mean BTS and snow depth values since 1996 at 3 sites in the Valais Alps. The annual number of BTS measurements is given in brackets.

(GFI), which is the sum of all daily negative ground temperatures measured during the winter and indicates how cold a winter is at the ground surface, and (c) the Mean Annual Ground Surface Temperature (MAGST), which is mainly the resulting effect of (a), (b), and summer temperatures.

Ground Freezing Index (GFI)
As for BTS measurements, the GFI values indicated that 2004/2005 and 2005/2006 were the two coldest years since the beginning of the measurement between 1995 and 2000 (Figure 4.3) for all sites with data available. The second winter 2005/2006 was the coldest at most of the sites. The GFI-values in 2004/2005 and 2005/2006 were 10–30% lower than the previous minimum.

Table 4.1: Measurements on the PERMOS BTS-sites in 2005 and 2006. BH: Borehole.

Site	Region	Available BTS	BTS 2005	BTS 2006	Mean 2000[1]	BH
Alpage de Mille	Val de Bagnes, VS	1996– …	7.03	9.03	yes	no
Lapires	Val de Nendaz, VS	2001– … [2]	15.03	n.a.	yes	yes
Réchy	Val de Nendaz, VS	2000–2004	n.a.	n.a.	yes	no

[1] 3- to 5-year average BTS map availabe

[2] with interruption in 2004 and 2006

Table 4.2: GST-sites and available data. GST-measurements: c/n + (i), n=total number of measurement places; c=complete series; i=incomplete series. BH=Borehole.

Site	Region	Available data	GST 2004/5	GST 2005/6	BTS	BH
Gemmi	Berner Oberland, VS	1994– …	16/38	8/38	no	no
Schilthorn	Berner Oberland, BE	1999– ...	(being processed!)		no	yes
Creux d.la Lé-Sanetsch	Berner Oberland, VS	1998–…	7/7	5/7+(1)	no	no
Ritord-Challand	Grand-Combin, VS	1997–…	20/22	21/22+(1)	no	no
Alpage de Mille	Val de Bagnes, VS	1997–…	18/18	18/18	yes	no
Lapires	Val de Nendaz, VS	1998–…	9/12+(1)	11/12	yes	yes
Yettes Condjà	Val de Nendaz, VS	1998–…	14/14	14/14	yes	no
Réchy	Val de Réchy, VS	1997–…	4/10+(6)	9/10	yes	no
Murtèl-Corvatsch	Upper Engadine, GR	2000–…	n.a.	n.a.	no	yes
Schafberg-Pontresina	Upper Engadine, GR	2000–…	5/9	4/9	no	yes

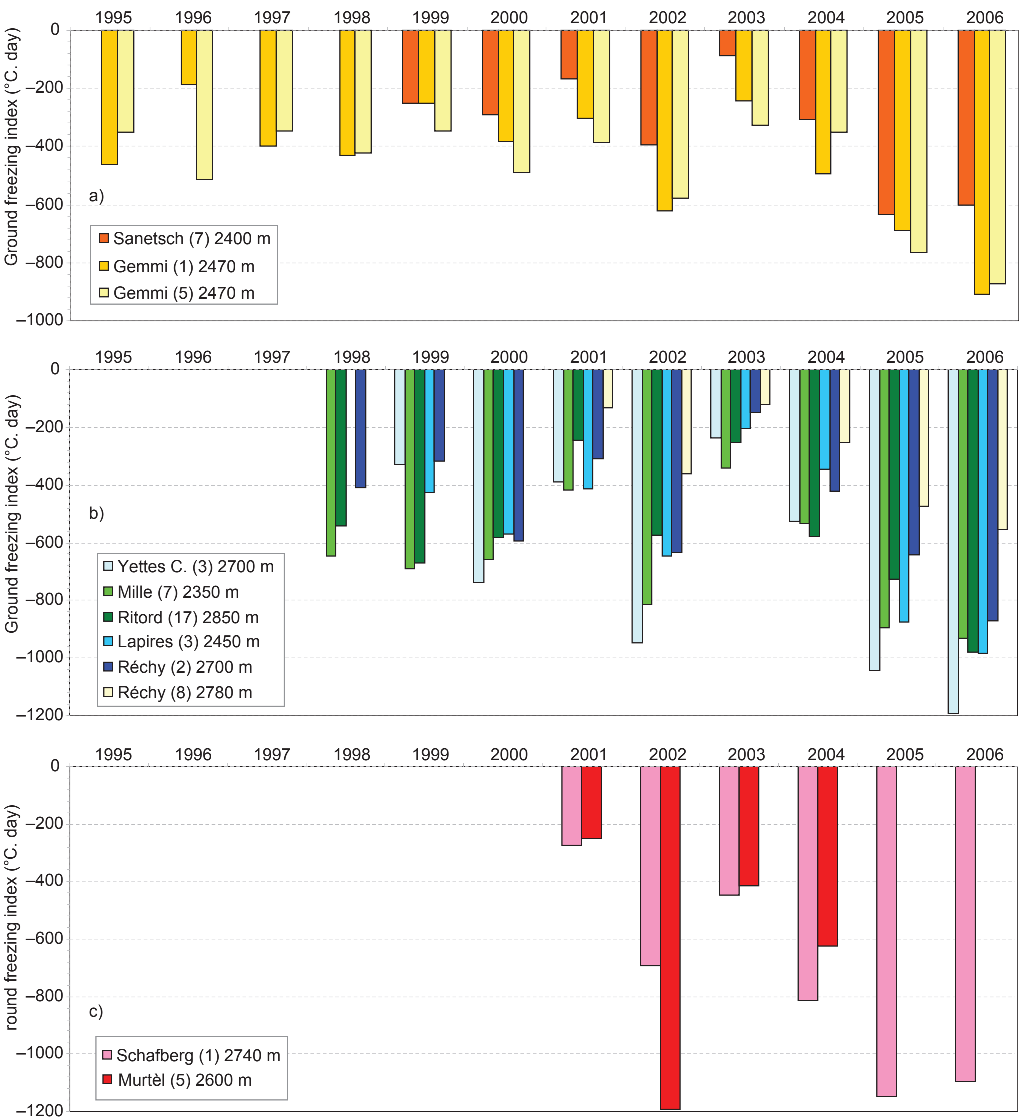

Figure 4.3: *Ground freezing index (GFI) at PERMOS GST-sites; a) Bernese Alps; b) Valais Alps; c) Upper Engadine. Legend: site-(total number of sensors)-mean elevation.*

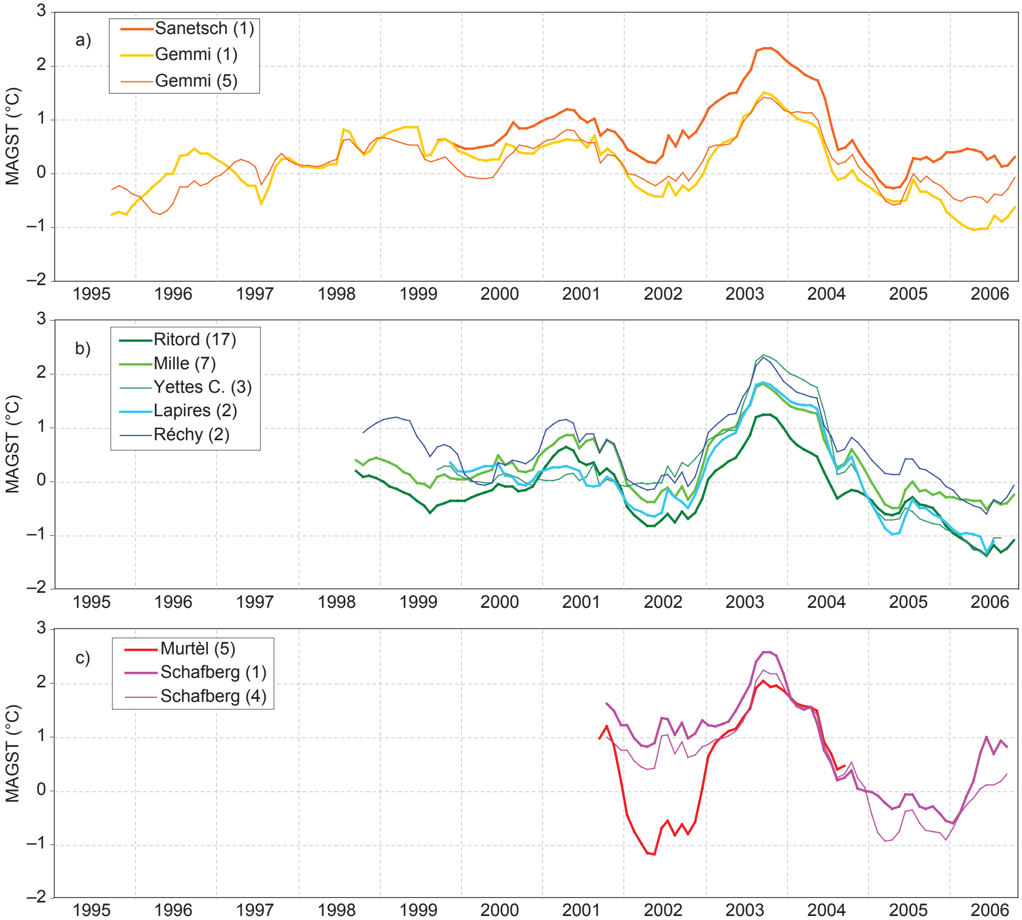

Figure 4.4: *Evolution of the mean annual ground surface temperature (MAGST) on PERMOS GST-sites; a) Bernese Alps; b) Valais Alps; c) Upper Engadine. MAGST is computed every month. Dates correspond to the end of the annual period used for the calculation. Legend: site-(total number of sensors).*

The low GST in 2004/2005 was due to the combined effect of the late snow cover in early winter, the rather thin snow cover in mid-winter and the prolonged cold period from the end of January to mid-March. The latter was the second coldest 50-day period at the Grand-St-Bernard Pass meteo station (2479 m a.s.l.) since 1935 (only a 50-day period in December 1963–January 1964 was colder). In the second winter snowfall was greater, but the prevalent low air temperatures in November/December intensified the cooling of the surface in early winter, making the GST as low as in the previous year for the whole winter at most sites.

Mean Annual Ground Surface Temperature (MAGST)

As a result of the two consecutive cold winters with low GFI-values, MAGST values continued the decrease since 2004 at all sites. The minimal MAGST values in 2005 or 2006 were the lowest since the beginning of the time series for all sites. The drop since the maxima in 2003 ranged between 2 °C and 3 °C. The earlier snowmelt in 2005, as compared to 2004, caused an increase of the MAGST of about 0.5 °C. The warmer summer 2006 produced a similar effect.

4.2 Rock Surface Temperatures (RST)

4.2.1 Introduction

Near-surface rock temperature was added to the measurement program of PERMOS in 2004 because a large proportion of Alpine permafrost exists in steep bedrock slopes (cf. Gruber and Haeberli, 2007), and yet, very little knowledge exists on ground temperatures or permafrost distribution in such terrain. Additionally, the hot and dry Alpine summer of 2003 – with many rock fall events originating from permafrost areas (e.g., Gruber et al., 2004a; Glaciological Report Permafrost, No. 4/5) – underscored the importance of steep bedrock permafrost. This section documents the procedures and the progress of near-surface rock temperature monitoring in PERMOS and provides baseline information for the interpretation of the data.

The measurements are intended to better characterize the spatial distribution of ground temperatures and permafrost in steep terrain and to document their changes over time. Additionally, they contribute to a tiered measurement setup at key PERMOS sites, where temperature measurements in boreholes are combined with distributed measurements of surface and near-surface temperatures in order to better understand the spatial variability of temperatures and the representativness of the borehole. This tiered approach also improves the validation of physics-based models (cf. Gruber 2005): steep bedrock maximizes the influence of topography on ground temperatures but has little snow and debris cover, gently sloping bedrock additionally includes the effect of snow cover, and debris-mantled slopes display further complicated effects of thermal offset.

4.2.2 Sites and Measurement Protocol

About 12 loggers were installed in 3 measurement areas of PERMOS: (a) Corvatsch, (b) Jungfraujoch/Schilthorn, and (c) Lapires/Bec de Bosson (Réchy) (Tables 4.3a–c, cf. Figure 4.1 for locations).

Rock temperatures are measured following Gruber et al. (2003): The measurement depth of 10 cm below the rock surface is a compromise between minimizing the influence of surface disturbances (cable, drill hole) on the measurements and minimizing the effort involved in drilling. Locations were chosen in order to sample different elevations, expositions to solar radiation, and to have some loggers in gently sloping bedrock with a winter snow cover. The area most interesting for measurements lies between 2500 and 3500 m a.s.l., where permafrost occurrence is spatially discontinuous

Photo 4: *Approach to the rock temperature loggers on the Jungfrau East Ridge. The loggers are installed on both, the north and south side of the ridge at 3750 m a.s.l. Photo: S. Gruber.*

Table 4.3a: *RST-sites at the Jungfraujoch-Schilthorn region.*

Code	Name	Responsible	Coordinates	Elevation (m)	Slope (°)	Aspect (°)	Skyview
CH_0001	Eigerfenster	UZH	643'307/159'034	2860	90	325	0.48
CH_0026	Birg east 2	UZH	632'285/156'996	2620	0	—	0.99
CH_0027	Schwarzgrat	UZH	630'495/156'597	2800	0	—	0.96
CH_0028	Engital	UZH	632'167/157'427	2410	10	130	0.88
CH_0029	Schilthornhütte	UZH	632'622/157'941	2450	0	—	0.93
CH_0030	Birg west 2	UZH	630'834/156'689	2680	22	130	0.92
CH_0031	Birg vertical	UZH	631'995/156'799	2670	85	205	0.48
CH_0032	Jungfrau ridge south	UZH	640'816/155'013	3750	70	145	0.57
CH_0033	Jungfrau ridge north	UZH	640'816/155'025	3750	55	344	0.77
CH_0034	Eismeer	UZH	643'830/158'049	3150	87	100	0.51
CH_0035	Mönch west ridge	UZH	642'189/155'603	3550	72	288	0.65

Table 4.3b: RST-sites at Murtèl-Corvatsch.

Code	Name	Responsible	Coordinates	Elevation (m)	Slope (°)	Aspect (°)	Skyview
CH_0014	Murtèl front	UZH	783'028/144'838	2630	15	20	0.93
CH_0015	Mandra south	UZH	784'607/145'527	2830	98	185	0.39
CH_0016	Mandra east	UZH	784'665/145'584	2805	90	88	0.47
CH_0017	Fuorcla	UZH	784'587/144'561	2740	11	344	0.97
CH_0018	Top gate	UZH	783'150/143'538	3285	72	333	0.65
CH_0019	Hubbel	UZH	783'822/145'760	2545	0	—	0.96
CH_0020	Middle flat	UZH	783'182/145'226	2690	8	320	0.99
CH_0021	Snow canon	UZH	783'463/145'390	2649	0	0	0.99
CH_0022	Middle ridge	UZH	783'370/144'916	2784	85	278	0.49
CH_0023	Top flat	UZH	783'100/143'413	3300	0	—	0.98
CH_0024	Top ridge	UZH	783'103/143'427	3300	58	181	0.73
CH_0025	Fuorcla north	UZH	784'615/145'365	2765	23	11	0.90

Table 4.3c: RST-sites at Lapires and Bec de Bosson (Réchy).

Code	Name	Responsible	Coordinates	Elevation (m)	Slope (°)	Aspect (°)	Skyview
CH_0002	BB-v01	UniFR	606'217/112'954	3100	90	75	0.46
CH_0003	BB-v02	UniFR	606'193/112'951	3120	75	308	0.57
CH_0004	BB-v03 (b)	UniFR	606'137/112'930	3140	95	198	0.45
CH_0005	BB-v04	UniFR	605'052/113'919	2590	85	278	0.48
CH_0006	BB-v05	UniFR	605'091/113'946	2590	90	50	0.41
CH_0007	BB-h01	UniFR	605'150/113'933	2600	0	—	0.99
CH_0008	La-v01	UniFR	588'670/106'300	2380	95	325	0.38
CH_0009	La-v02	UniFR	587'740/106'089	2730	95	39	0.39
CH_0010	La-v03	UniFR	587'767/106'142	2720	90	140	0.43
CH_0011	La-v04	UniFR	587'558/105'773	2700	80	225	0.55
CH_0012	La-v05	UniFR	587'693/105'622	2770	100	341	0.36
CH_0013	La-h01	UniFR	587'650/105'875	2735	0	—	0.99

and strongly dependent on topography. At each site, the local placement of sensors is important: The facet in the rock wall chosen for measurement should resemble the general character of the large face as close as possible. Near-vertical situations are preferable due to a minimum snow cover and a vertical distance of several meters should be maintained to any flatter terrain below the monitoring sites in order to avoid burial by accumulating snow. Homogeneous surfaces that are free of visible discontinuities within a radius of >30 cm are preferred. Additionally, fast and safe access to the sites is important to minimize effort and cost of maintenance. However, not all sites can accommodate this even during bad weather and, sometimes, data cannot be recovered as planned because safety must have absolute priority. The compromise between optimal placement for measurements and maintenance is sometimes difficult to achieve.

The data loggers used are Geoprecision M-Log4 (Photo 6), specifically developed for this purpose and following the geometry and installation procedure outlined by Gruber et al. (2003). The loggers have an accuracy of +/– 0.05 °C at 0 °C. The non-volatile memory holds 100,000 measurements and data can be offloaded from the installed logger via an infrared port. The 85x20 mm steel housing is IP68 waterproof, the lithium battery allows for five years of operation down to –50 °C. Initially, the measurement interval has been set to 10 min., allowing for nearly two years of inde-

Photo 5: Accessing the data logger below the Eigerfenster: This site has good access with the Jungfraubahn railway and is safe from rock fall and avalanches even in bad weather due to a large overhang above. Photo: S. Gruber.

Photo 6: M-Log4 data logger installed in a rock face. The body of the logger is held by two hydraulic hose brackets (blue) and two screws anchored in wall plugs. Photo: S. Gruber.

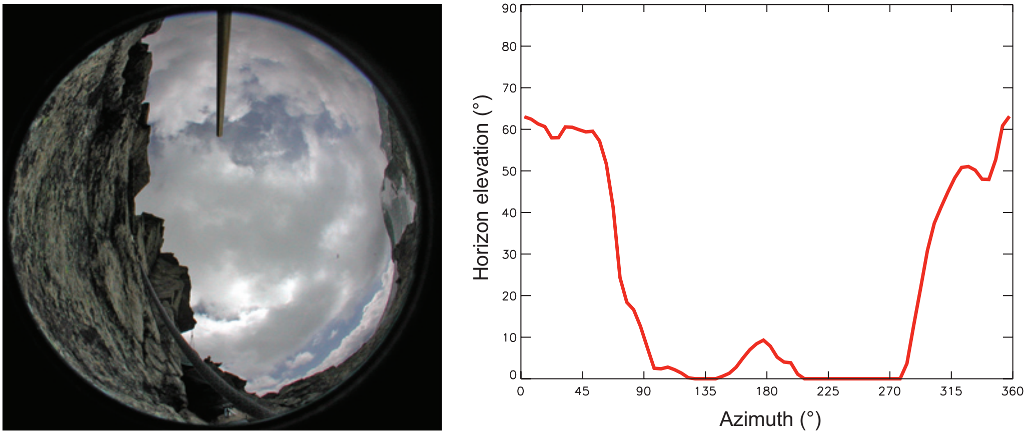

Figure 4.6: *Fish-eye photograph and the derived horizon line. The elongated vertical object in the top of the image is a marker to reference the azimuth of the image. The horizon line is important for the calculation of solar radiation and the sky view factor.*

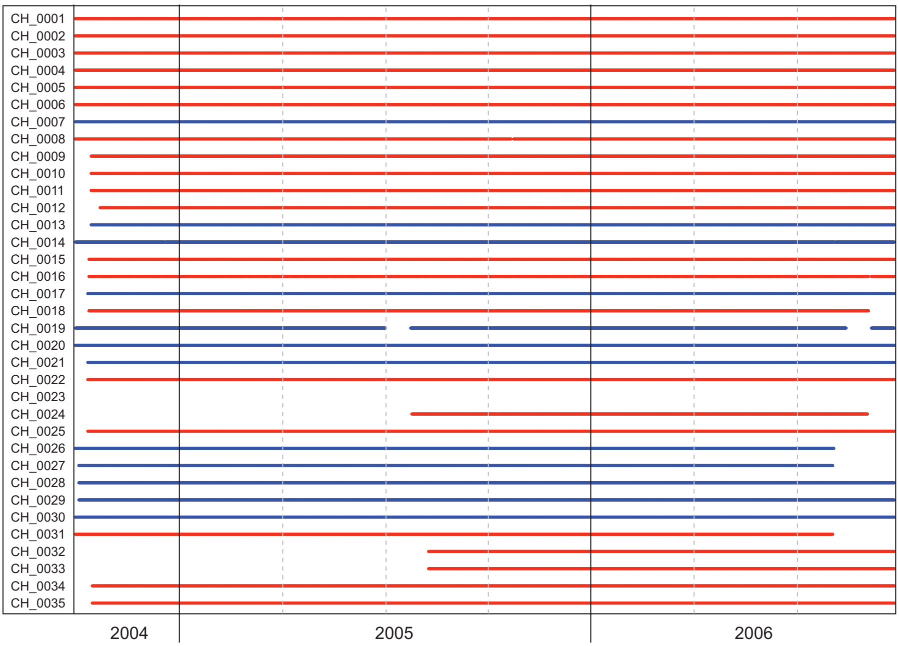

Figure 4.7: *Available measurements for each location within the reporting period. Blue lines indicate gently inclined bedrock and red lines indicate steep bedrock. Cf. Table 4.3a–c for details about each site.*

pendent operation. Recently, the interval has been changed to 30 min, after analyses showed that this only results in negligible loss of information.

At each site, a set of additional data is recorded that is necessary for sound interpretation or modeling of the measured temperatures: Elevation, aspect, slope angle of the rock facet are measured and a fish-eye photograph (Photo 6) is taken, from which local horizon lines and, based on this, the sky-view factor (i.e., the percentage of sky visible at the logger location) are extracted. For individual sites, rock albedo has been measured in the laboratory.

4.2.3 Data

The most important post-processing steps of the data are: (a) the time deviation of the logger clock is corrected assuming a linear drift; (b) raw values are resampled to hourly resolution and for each hour the time difference to the nearest measurement is recorded as a quality parameter; (c) measurements and the quality parameter are aggregated to daily and annual resolution; (d) selected additional information (e.g., the elevation of the 0 °C isotherm) is computed; and (e) a summary table is generated. Figure 4.7 displays the measurements available for the reporting period.

Figure 4.8 shows a synopsis of measurement results for the reporting period 2004/2005 and 2005/2006. Temperatures are converted to elevations of the hypothetical 0 °C isotherm using the site elevation and a lapse rate of –0.0065 °C/m. This allows a simple comparison of the conditions at the diverse measurement sites without the need to consider site elevations when comparing measured temperatures. The aspect of steep bedrock sites is colour-coded via the degree of north exposure of a site, thus not differentiating between eastern and western intermediate aspects. Sites with a gentle inclination and significant winter snow cover are shown in light gray. Temperatures are boxcar filtered over a width of 365 days and only values based on a full set of 365 consecutive days are shown. It is easily seen that the vertical range (or lateral, topography-induced variability) of permafrost distribution limits inferred from those measurements in solid bedrock is up to 2000 m. As expected, southern aspects have much higher limits than northern aspects. Similarly, measurements in gently sloping bedrock indicate a vertical range of around 1000 m. While this is a very intuitive way to visualize temperatures and their approximate relation with permafrost and topography one should keep in mind that this is a way to look at measurements and not a graph showing permafrost distribution. Especially when subject to snow cover, lapse rates of ground temperatures may be very different from the atmospheric lapse rate assumed, and, at some stage, the computed isotherm elevation for gently sloping ground may already be above the regional equilibrium line of glaciers and, thus, be only a hypothetical point. Plots of individual high-resolution temperature time series are shown in Figure 4.6 of the Glaciological Report Permafrost No. 4/5 (2007) as well as in the report in «Die Alpen» (2007).

4.2.4 Interpretation and Use of Near-surface Rock Temperatures

Assuming only minor changes in mean annual temperatures with depth (thermal offset) in solid rock, near-surface temperature measurements are a useful proxy for permafrost occurrence. However, the interannual variability of temperatures is considerable and, as a consequence, long-term

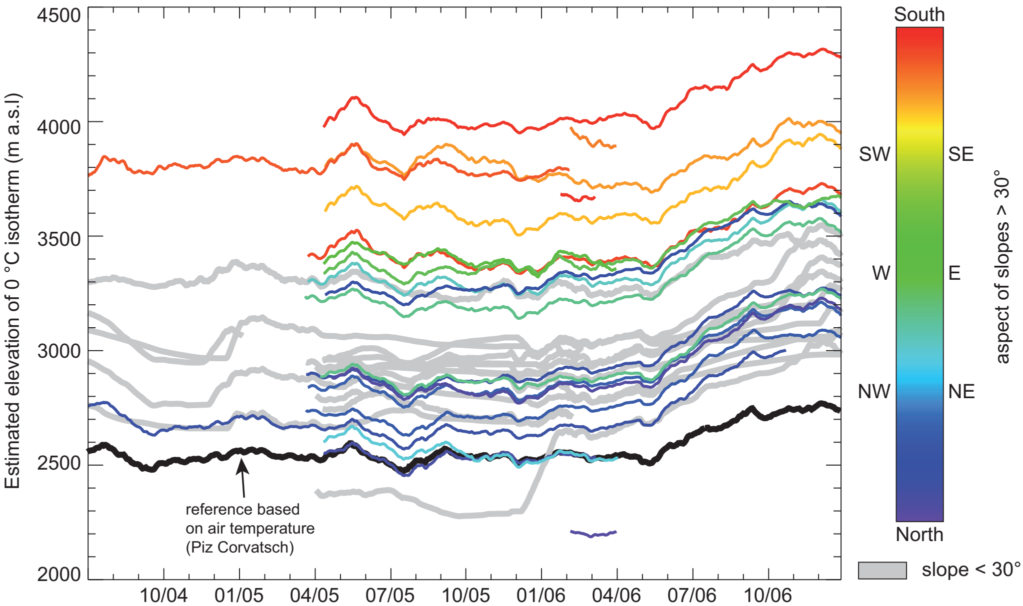

Figure 4.8: *Synopsis of measurement results: Temperatures have been converted to elevations of a hypothetical 0 °C isotherm assuming a lapse rate of –0.0065 °C/m and filtered using a 365-day boxcar average. This gives an approximate visual impression of the permafrost limits and their spatial variability as inferred from two years of measurements in exposed bedrock.*

measurements or strategies to estimate mean temperatures over decades rather than individual years are needed for the delineation of permafrost. One strategy is the use of process-based models of rock temperature that, once validated, can be used to simulate rock temperatures during the over 25 years that detailed meteorologic data is available for MeteoSwiss sites such as Corvatsch or Jungfraujoch (cf. Gruber et al., 2004b). A further and simpler method is to assume the long-term temporal component of temperature variability to be represented by air temperature and the spatial differentiation to be represented by short term rock temperature measurements (one or few full years). Using this linear separation, rock temperatures measured over one or only a few years can approximately be normalized to a reference period (long-term) by subtracting the difference between the short term and long term MAAT from the mean measured rock temperature at one site.

When applying the measured temperatures or derived model results to the real world, however, one needs to be aware of the bias inherent in the sampling design (cf. Gruber and Haeberli, 2007): By only measuring near-vertical and non-fractured bedrock, we neglect the largest portion of bedrock permafrost slopes: 40–60° steep slopes with significant fracturing, some debris cover and intermittent snow cover. Both, intermittent and thin snow cover and debris/fracturing can be expected to result in lower ground temperatures than those measured by PERMOS. Similarly, a changing degree of water/ice/air content in the fracture and pore space of the active layer can result in thermal offset, making temperatures at depth lower than those measured at the surface. To avoid a bias it would be necessary to instrument and maintain boreholes of 5–10 m depth in terrain that is very difficult and dangerous to access. While individual boreholes like this would be very desirable, modeling experiments are currently the most promising avenue for constraining the possible effect of this sample bias.

4.3 Conclusions Surface Temperatures

Ground Surface Temperatures (GST)

Ground surface temperature in unconsolidated sedimentary terrain were low in both years 2004/2005 and 2005/2006, particularly during winter. Ground freezing indeces and BTS values were the coldest since the start of systematic observations 6–12 years ago. MAGST dropped consecutively in 2005 and/or 2006 to new minima 2–3 °C colder than the maxima in 2003. At the end of the hydrological year 2005/2006, MAGST rose again to about the level of to the mean value of the past decade.

Rock Surface Temperatures (RST)

The near-surface rock temperature measurements presented are already being used by scientists. In part they contributed to successful temperature modeling at the Zugspitze, Germany (cf. Noetzli, 2008), and comparison with GST measurements in coarse blocks on rock glacier Murtèl has helped to discover a new mechanism partly responsible for the cooler temperatures measured in block fields when compared with bedrock (Gruber and Hoelzle, 2008). Once several years of measurements are available, the different reactions off diverse terrain will be more easily assessed using a comparison with the existing PERMOS GST time series.

The measurement of near-surface rock temperatures for monitoring purposes and the investigation of permafrost processes is a rapidly growing field of research: Recently, similar studies of near-surface rock temperatures have also been initiated in France, Italy, Austria, Norway, Canada, and New Zealand, and may later on provide a valuable comparison with PERMOS data.

Partly based on experience with rock temperature measurements and partly motivated by the prospect of pioneering next-generation technology for PERMOS, the PermaSense project (www.permasense.ch) funded by FOEN and the SNF NCCR-MICS is currently developing wireless sensor networks for mountain permafrost research (e.g., Hasler et al., 2008), which may help to make these kind of measurements more operational and effective.

5 Air Photos

5.1 Air Photos in 2004/2005 and 2005/2006

Aerial photographs are collected for documentation purposes and photogrammetric analyses. Several areas have been flown regularly since the 1980s (Tables 5.1 and 5.2, Figure 5.1). In the reporting period, aerial photos were taken only from the Gruben site.

For photogrammetrical interpretation and analysis, aerial photos have to be taken in a regular cycle. Information about surface phenomena at a certain time is abundant on aerial photos which allows quantification of different parameters, e.g., using photogrammetry.

Figure 5.1: Areas where air photos are taken regularly.

Table 5.1: 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	Max. speed	Available years
Murtèl	low f. h., b-w	15 cm/a	1987, 1988, 1991, 1995, 1996, 2002
Muragl	low f. h., b-w	50 cm/a	1981, 1985, 1990, 1994, 1998, 1999, 2000, 2002
Schafberg	low f. h., b-w	10 cm/a	1991, 1994, 1998, 1999, 2000
Réchy	low f. h., b-w		1986, 1991, 1995, 1999, 2004
Gruben	low f. h., b-w	100 cm/a	1967, 1975, 1983, 1985, 1988, 1989, 1990, 1991, 1992, 1994, 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006
Suvretta	low f. h., b-w	200 cm/a	1992, 1997, 2002
Gross Gufer	low f. h., b-w	250 cm/a	1987, 1994, 2000
Furggentälti	low f. h., b-w	300 cm/a	1990, 1995, 1999, 2000

Table 5.2: Available infrared air photos.

Region	IR-air photos
Morteratsch	1981
Goms North	1983
Goms South	1983
Goms-Gerental	1983
Goms-Münsterbach	1983
Upper Engadine-Julier	1988
Upper Engadine-Val Roseg	1988
Piz Quattervals	1984
Piz Vadret-Piz Fora	1984
Vals da Camp	1984
Val Maroz-Julier-Piz Ot	1984
Roseggletscher	1985, 2004
Val Réchy-Moiry	1986
Simplon	1987
Turtmann-Zinal	1987
Mattertal	1991
Saastal	1991
Simplon-Almagell	1991
Flüelapass	1997

6 Conclusions

During the reported period 2004/2005 and 2005/2006 the initial three key elements were continued and complemented and adapted as follows: (1) at several drill sites fixed electrodes were installed to allow electrical resistivity tomography (ERT) monitoring which complement ongoing borehole measurements; (2) ground surface temperature measurements in both loose debris and rock surface temperatures were initiated, and (3) data from aerial photographs were utilized, especially for the quantification of rock glacier movements. These adaptations are important and in line with the concept of the pilot phase. Although parameters within a monitoring programme should be kept homogeneous, it is even more important to ensure that the observed parameters are meeting the goal. The adaptations illustrate the flexibility of the PERMOS approach.

Weather conditions at the beginning of the period were important since lower than average snow thickness in both winters 2004/2005 and 2005/2006 cooled the subsurface considerably. Low air temperatures in the winter 2004/2005 caused further permafrost cooling, enforcing permafrost cooling even further. Therefore, at most sites, ground freezing index (GFI) during the two years was higher than previously observed within PERMOS. Similarly, at Alpage de Mille, the lowest Bottom Temperature of the Snow cover (BTS) was measured since the beginning of the monitoring (1996). All drillings and BTS sites are in low gradient locations with a thick snow cover in winter. However, a considerable part of Alpine permafrost is spread in areas where little or even no snow accumulates because of wind or avalanches, or because it is simply too steep. It is for this reason, that PERMOS also incorporated rock surface temperature sites, which probably should be complemented in future by a borehole in a steep or vertical location. At about 10 m depth, weather conditions caused an inversion of the warming trend generated between the cold winter 2001/2002 and in particular the extreme summer 2003. Temperature values reached similar values as in 2001, at some locations even colder. Aerial photos were conducted within the planned rotation, i.e., during the reporting period at Gruben.

At the PERMOS sites, most of which accumulate a snow cover in winter, MAGST fell by about 0.5–1.0 °C during the two years of reporting. Permafrost temperatures dropped after the extreme summer 2003 to similar values as those recorded in 2002.

7 Selected Aspects of Permafrost Monitoring

The recent acceleration of rock glaciers in the Swiss Alps was introduced in the chapter on aerial photographs in the last report (Glaciological Report Permafrost, No. 4/5). Current decadal surface velocities are roughly two times faster than in the 1970–1980's. The present chapter focuses on special aspects of rock glacier kinematics within this context of increased activity. The first section (Section 7.1) is dedicated to short-term (i.e., seasonal, interannual) variations of the surface motion of rock glaciers measured during the 2004–2006 period at PERMOS sites. Observations and first systematic measurements on destabilized rock glaciers are presented in Section 7.2.

7.1 Short-term Variations in Rock Glacier Kinematics

Kinematics are quantified by photogrammetric methods for a period of several years (6 or 7 years, depending on the frequency of flight campaigns). The total amount of movement is then divided by the years to get average annual information on displacements. Large fluctuations can, however, occur during the time interval both, interannually and seasonally. To quantify annual values or describe seasonal changes in kinematics, additonal methods (e.g., terrestrial geodetic survey (total station) or differential GPS measurements) have to be applied.

7.1.1 Interannual Variations

Repeated geodetic measurements on PERMOS rock glaciers were made earlier; between 1979 and 1982 annual measurements were conducted on Gruben rock glacier (Haeberli, 1985) and seasonal changes were quantified for Muragl rock glacier (Kääb, 2005). Based on recent observations of rock glacier kinematics, annual terrestrial surveys of rock glacier surface motion have been carried out on several PERMOS sites for a few years (Table 7.1, Figure 5.1). The surveys, which have to be repeated at least once a year at approximately the same date (in late summer), started already in 1994 on the Furggentälti/Gemmi rockglacier, which is the longest available series (Krummenacher et al., 2008). Measurements have been carried out since 2000, 2001, or 2002 on the Yettes Condjà and Becs-de-Bosson/Réchy rock glaciers and on the Aget push-moraine (Lambiel and Delaloye, 2004) and on two landforms in the Turtmann Valley (Roer, 2005). On the Muragl rock glacier, interannual surveys were already performed between 1998 and 2003 (Kääb, 2005). No continuous or more recently started time series are also available for other rock glaciers in the Swiss Alps, as for instance the Trais Fluors/Büz North rock glacier in Upper Engadine (Ikeda et al., 2008).

From these measurements, interannual variations in horizontal displacement as well as changes in the vertical component of movement (which are more difficult to interpret, e.g., Lambiel and Delaloye, 2004; Roer, 2005) can be described for entire or parts of the rock glaciers. The data has shown different magnitudes of movement (Table 7.2), but relative changes since 2002 have been similar

Table 7.1: List of PERMOS sites with terrestrial survey for the period 2000–2006.

Site	Region	Method	Measurements 2000	2001	2002	2003	2004	2005	2006
Gemmi	Bernese Alps, VS	Total station	x	x	x	x	x	x	x
Yettes C.	Val de Nendaz, VS	Differential GPS	x	x	n.a.	x	x	x	x
Becs/Bosson	Val de Réchy, VS	Differential GPS	n.a.	x	n.a.	x	x	x	x
Aget	Val de Bagnes, VS	Differential GPS	n.a.	x	n.a.	x	x	x	x
HuHH1	Turtmann Valley, VS	Total station	n.a.	x	x	x	x	x	n.a.
HuHH3	Turtmann Valley, VS	Total station	n.a.	n.a.	x	x	x	x	x
Muragl	Upper Engadine, GR	Total station	x	x	x	x	n.a.	n.a.	n.a.

Table 7.2: Characteristics of rock glaciers with annual surface velocity survey on PERMOS sites (Delaloye et al. 2008a, adapted)

Site	Elevation m a.s.l.	Surface km^2	Aspect	Horizontal velocity 03/04 $m\ a^{-1}$	Relative drop 04–06 %
Gemmi	2450–2650	0.03	N	3.08	–52
Yettes C. B	2600–2740	0.02	NE	1.20	–81
Yettes C. C	2620–2820	0.05	N	0.22	–42
Becs-de-Bosson	2610–2850	0.10	NW	0.97	–36
Aget	2810–2890	0.03	SE	0.20	–50
HuHH1	2630–2780	0.04	NNW	1.26	n.a.
HuHH3	2515–2650	0.05	NW	1.78	–52

and have occurred very synchronously throughout the regions (Figure 7.1). They are also concomitant with data from the French and and Austrian Alps (Delaloye et al., 2008a). The comparison of the velocity changes with local parameters of the landforms (i.e., slope, length, and altitude) revealed no significant correlation (Roer, 2005). Delaloye et al. (2008a) stated that the observed synchronous and similar interannual variations were primarily related to external climatic factors rather than to internal characteristics of the rock glaciers. Indeed, the horizontal velocity changes have been mostly well correlated with shifts of the mean annual ground surface temperature (MAGST) – used as a proxy for the temperature in the upper permafrost layers – with a delay of a few months. The delay would reflect mostly the influence of the slow propagation of the thermal signal at the surface into permafrost on the creep process. Seasonal factors may also play a significant role on annual velocities. For example, a larger winter snow accumulation, which produces more meltwater in spring, appears to facilitate a higher rate of rock glacier motion (e.g., Ikeda et al., 2008).

Due to early snow fall in autumn 2002 and the extremely warm summer 2003, MAGST was the highest of the last decade in 2002/2003 (cf. Chapter 4). Maximum velocities were measured in 2003/2004 on all rock glaciers considered here (Figure 7.1, Table 7.2). Horizontal velocities decreased drastically on all rock glaciers during the 2004–2006 period. The drop reached about 50% and seems to be related to the significant cooling that occurred at the ground surface after 2003 (see Chapter 4). The annual acceleration of the Mont Gelé B/Yettes Condjà rock glacier was particularly strong in 2003/2004 (+ 100%), as well as the drop in velocity during the two following years (the mean velocity in 2005/2006 was only 20% of the 2003/2004 value). The low velocities of 2003/2004 may be due to changes in the hydrological properties of the rock glacier (increase of water infiltration), which may have provoked time-limited destabilization of the landform (a scar probably corresponding to the upper limit of a shear horizon is located in the upper part of the rock glacier).

From the available data, it appears that strong changes in deformation rate of rock glaciers are occurring and even if the factors controlling these changes are still not precisely known it was decided to include the terrestrial measurements of annual velocities into the PERMOS network (under the aspect of «Permafrost Dynamics», together with the information from aerial photographs) from 2007 on. The data will provide valuable information for both, the scientific understanding of permafrost creep processes and the assessment of natural hazards related to unconsolidated frozen material on steep slopes.

7.2.2 Seasonal Variations

Measurements on the Gruben rock glacier in the early 1980s already indicated that strong short-term velocity variations might occur where the permafrost base in a rock glacier is above bedrock and that these variations could be different in various rock glacier parts (Haeberli, 1985). Seasonal variations of surface displacements have then been reported for several other rock glaciers (Kääb et al., 2003; Hausmann et al., 2007, Perruchoud and Delaloye, 2007), whereas almost constant annual velocities have also been observed (Krainer and He, 2006), particularly where permafrost reaches into bedrock as on the Murtèl rock glacier (Haeberli et al., 1998).

Seasonal fluctuations can be relatively large, up to more than +/-50 % around the annual mean (Figure 7.2). They occur each year more or less at the same time but are not fully synchronous for all rock glaciers. Highest velocities are, however, reached in most cases between summer and early winter, whereas lowest values are usually observed in spring or early summer. The seasonal increase in velocity can be rapid and connected to the snowmelt phase as on the Becs-de-Bosson and Gemmi/Furgentälti rock glaciers (Perruchoud and Delaloye, 2007, Krummenacher et al., 2008) or progressive and delayed as on the Muragl rock glacier (Kääb, 2005). On the latter, the annual amplitude of the seasonal rhythm varies significantly, the winter/spring decrease being reduced by warmer winter ground surface temperature (Kääb et al., 2007).

During the report period 2004/2006, seasonal measurements were initiated on the entire Becs-de-Bosson rock glacier. The position of about 100 marked boulders was surveyed 6–8 times a year, allowing a detailed analysis of short-term variations of velocities. After two years of measurements,

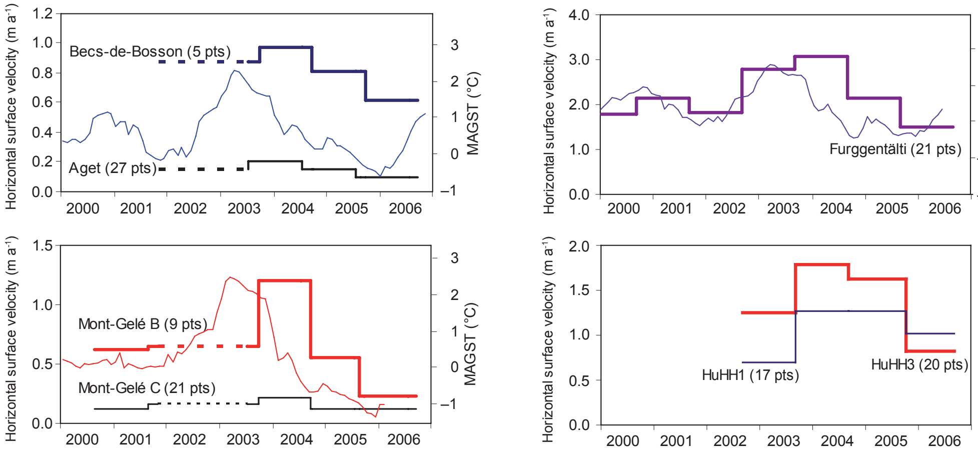

Figure 7.1: *Annual horizontal surface velocities of rockglaciers in the western Swiss Alps (mean value of the number of measurement points indicated in brackets) and in situ mean annual ground surface temperature (MAGST) (Delaloye et al., 2008a, modified). MAGST is computed every month. Dates correspond to the median of the 12-month period used for the calculation.*

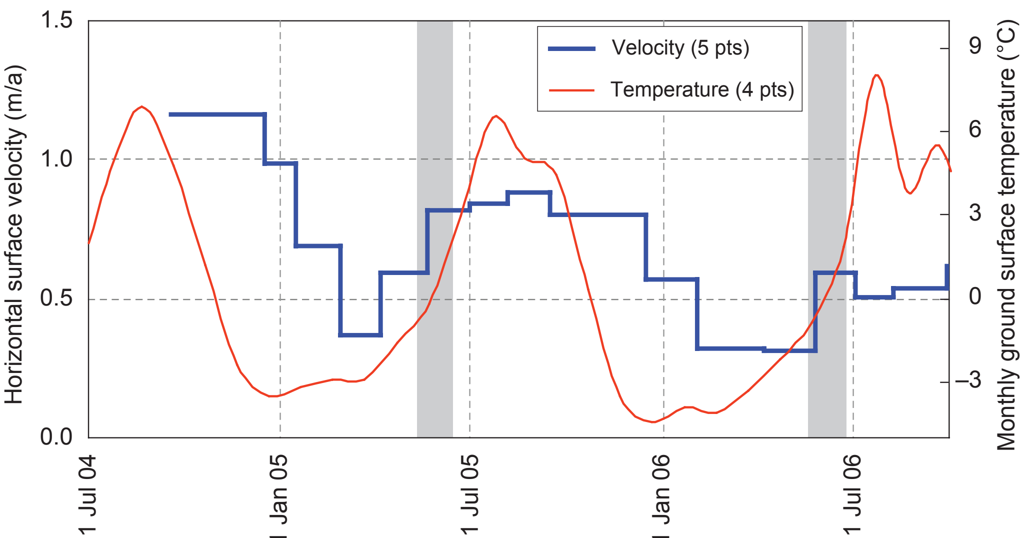

Figure 7.2: *Seasonal horizontal velocities and monthly ground surface temperature on the Becs-de-Bosson/Réchy rock glacier (Perruchoud and Delaloye, 2007, adapted). In brackets, the number of measurement points. Snowmelt periods in grey.*

Photo 7: The destabilized terminal section of the Petit-Vélan rock glacier in Aug 2005 (Grand-St. Bernard area). The front moved about 30 m downward from 1995 to 2008. Photo: R. Delaloye.

strong seasonal fluctuations have been observed that appear to repeat every year with approximately the same rhythm (Figure 7.2) (Perruchoud and Delaloye, 2007). A gradual winter-spring velocity decrease occurs 1–3 months after the seasonal cooling of the ground surface temperature. The velocity increases rapidly by the end of the spring quite simultaneously with the snowmelt period. The seasonal increase occurred slightly later in 2006 than in 2005. This may be linked to the snowmelt period, which began about two weeks later in 2006 (cf. Chapter 2.4). It was also shown that the seasonal fluctuations were not perfectly synchronous on the entire rock glacier. These results indicate that seasonal ground surface temperature and meltwater (increased water pressure at depth in early summer?) might play a significant role in the kinematics of some rock glaciers. These processes have to be further investigated in the future.

7.2 Destabilized Rock Glaciers

Some rock glaciers in Switzerland have experienced severe changes in their kinematics, geometry and/or topography over the last years or decades. At present, about 15 Alpine rock glaciers have been identified as destabilized features (Delaloye et al., 2008b; Lambiel et al., 2008; Roer et al., 2008). Besides high horizontal velocities and advance rates, many rock glaciers considered in this category show distinct cracks (up to 14 m deep, located either in the rooting zone or closer to the front), indicating deep sheer-zones similar to those known for rotational landslides, as well as extraordinary changes at their front (Figures 7.3–7.4). The cracks indicate a change from permafrost creep to landslide-like mass wasting. Despite the limited knowledge on rock glacier dynamics, the principle hypothesis is that the rheological properties of warming ice and the resulting changes

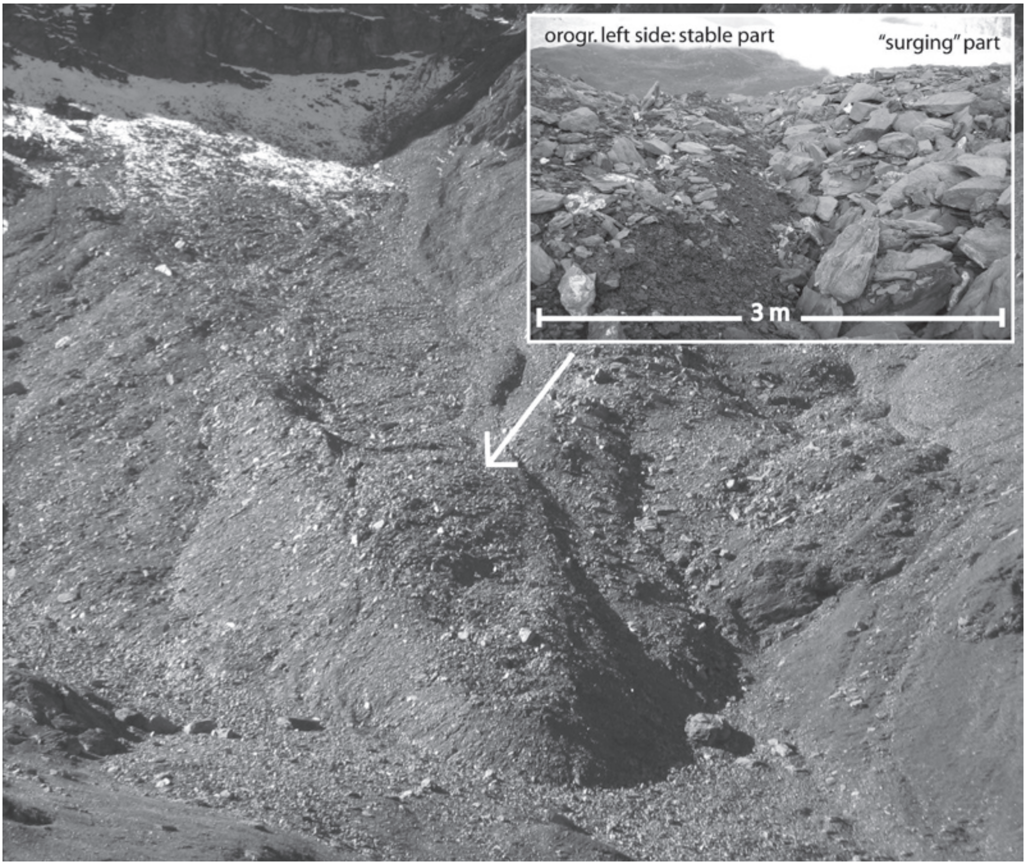

Figure 7.3: Rock glacier Tsaté-Moiry. Several scars, developing since the 1980s, are found all over the landform. Velocities at the front were about 5 m/a between 2005 and 2006 (Photos: C. Lambiel, 2007).

in the stress-strain relation control the development of cracks and destabilization of rock glacier tongues. In addition, hydrological effects (e.g., unfrozen water) in the permafrost body or at its base may contribute to the initiation of rapid flow acceleration in tertiary creep (Roer et al., 2008).

The extraordinarily high velocities of a collapsing landform were first described for the rock glacier Grueo1 in the Turtmann Valley by means of digital photogrammetry (Roer, 2005). First systematic terrestrial measurements on the kinematics of destabilized rock glaciers then started in summer 2005 on the Petit-Vélan and Tsaté-Moiry rock glaciers (Delaloye et al., 2008b). Maximum horizontal velocities measured in 2005/2006 were 5 m a^{-1} on Tsaté-Moiry landform (Anniviers Valley, Valais Alps) and 3.5 m a^{-1} in the terminal section of the Petit-Vélan rock glacier (Grand St.-Bernard area, Valais Alps).

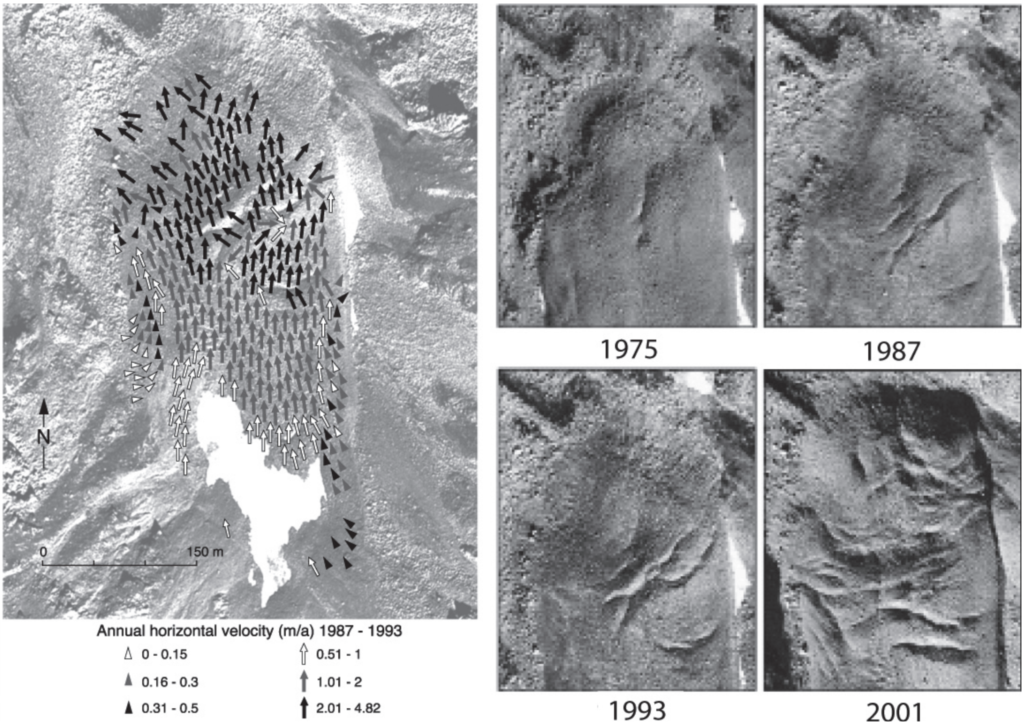

Figure 7.4: *Collapsing tongue and development of crevasses between 1975 and 2001 of rock glacier Grueo1 (Valais, Switzerland). Crevasses started to build on the orographic right side. Between 1993 and 2001 the surge-like movement spread all over the tongue. Between 1975 and 2001 the rock glacier advanced ca. 60m (~2.3m per year). (See also Roer, 2007, Kääb et al., 2007). Orthoimages of 1975, 1987, and 1993 © Swiss Federal Office of Topography (Swisstopo). Orthoimage of 2001 © RTG 437, Department of Geography, University of Bonn.*

7.3 Conclusions Rock Glacier Kinematics

The acceleration of rock glacier surface velocities in the past two decades and the destabilization of several landforms show that permafrost creep conditions are changing in the Alps. The transfer of loose sediment on Alpine periglacial slopes is increasing. It is therefore a challenging task for a monitoring program like PERMOS to document the variations of the rock glacier dynamics for the coming years and decades. Moreover, data collected since a few years on seasonal and interannual variation of rock glacier kinematics in the Alps show that significant changes can occur at short time interval, but that they can be relatively homogeneous throughout the entire Alpine range.

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These institutes perform all fieldwork and maintain the PERMOS sites. They therefore contribute significantly to the development of the highly valuable and essential network that makes the Permafrost Monitoring Switzerland possible. The present report is a compilation from a number of contributors of data, text, illustrations, and photos, as can be seen in the imprint. In addition, there are numerous field assistants who helped to obtain data as well as generous support from the following companies: Corvatsch-Furtschellas Bahnen, Jungfraubahnen, High Altitude Research Station Jungfraujoch, Luftseilbahn Leukerbad-Gemmipass, Schilthorn Bahnen, Téléverbier, and Télénendaz.

Finally, our thanks go to all who supported PERMOS in any way and enabled this report.

Photo 8: Measurement site Réchy. Photo: R. Delaloye.

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Appendix

Boreholes

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Arolla, Mt. Dolin 01/96 and 02/96

Site	
Description	Arolla, Mt. Dolin, VS
Coordinates	01/96: 601246/97232, 02/96: 601257/97248
Elevation (m a.s.l.)	01/96: 2840, 02/96 2820
Slope angle (°)	38-40
Slope aspect	NE
Morphology	Scree slope
Lithology	Dolomite
Vegetation	No vegetation
Borehole	
Drilling date	1996
Depth (m)	10
Chain length (m)	5.5
Thermistor depths (m)	0.5, 1.5, 2.5, 3.5, 5.5
Thermistor type	YSI 46008 + Campbell CR10X
Last calibration	1996
Responsible	SLF, M. Phillips
Other measurements	BTS/GST
Comments	Snow nets
Available data	Since 1996

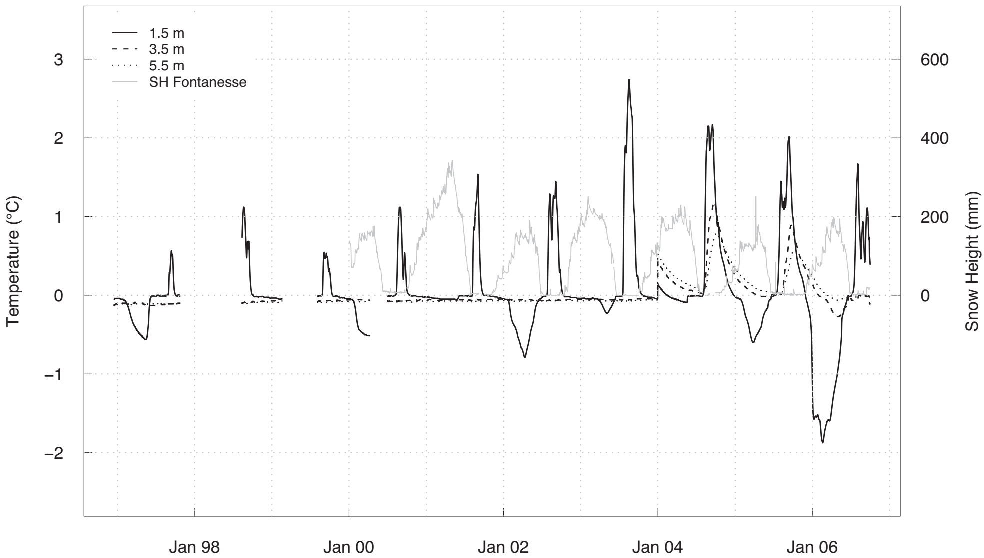

Fig. A.1: *Temperature-time-plot of the borehole Arolla 01/96 for the thermistors at 1.5, 3.5, and 5.5 m depth. Additionally, the snow height at Fontanesse is displayed.*

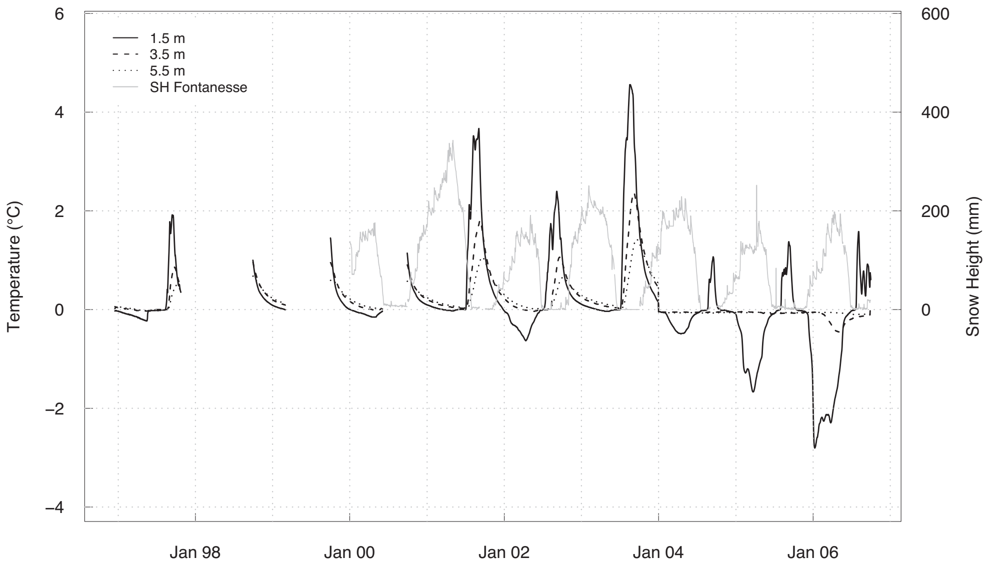

Fig. A.2: *Temperature-time-plot of the borehole Arolla 02/96 for the thermistors at 1.5, 3.5, and 5.5 m depth. Additionally, the snow height at Fontanesse is displayed.*

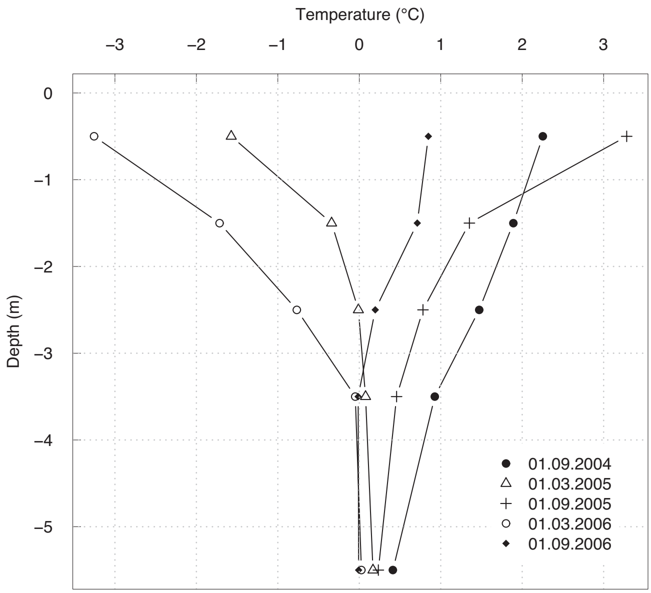

Fig. A.3: *Temperature profiles for Arolla 01/96.*

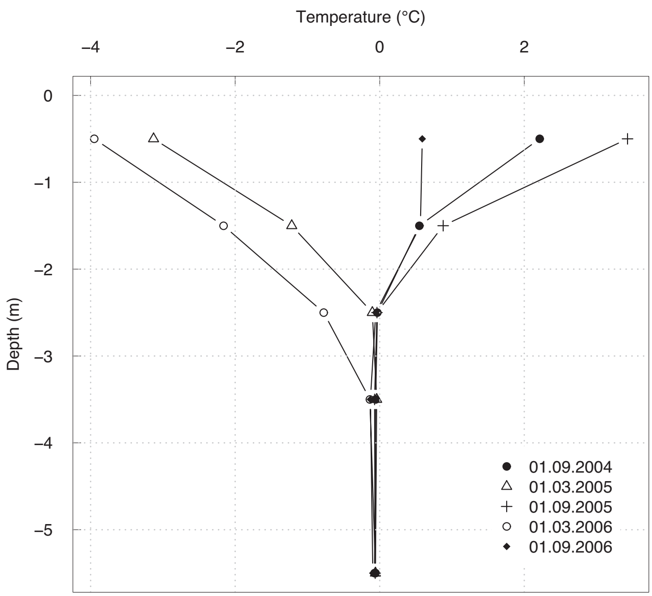

Fig. A.4: *Temperature profiles for Arolla 02/96.*

Flüela 01/02

Site	
Description	Flüelapass Schottensee, GR
Coordinates	791375/180575
Elevation (m a.s.l.)	2394
Slope angle (°)	26
Slope aspect	NE
Morphology	Scree slope, slope base
Lithology	Amphibolit, paragneiss
Vegetation	No vegetation
Borehole	
Drilling date	19.8.2002
Depth (m)	23
Chain length (m)	20
Thermistor depths (m)	0.25, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 6.0, 8.0, 10.0, 15.0, 20.0
Thermistor type	YSI 46006 + Campbell CR10X
Last calibration	1.10.2002
Responsible	SLF, M. Phillips
Other measurements	–
Comments	–
Available data	Since 2002

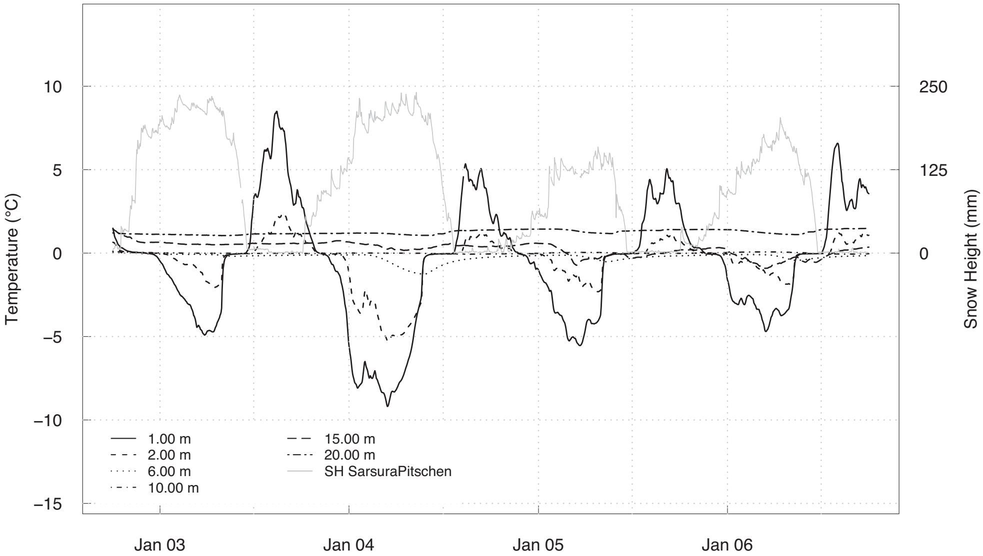

Fig. A.5: *Temperature-time-plot of the borehole Flüela 01/02 for the thermistors at 1.0, 2.0, 6.0, 10.0, 15.0 and 20.0 m depth. Additionally, the snow height on Sarsura Pitschen is displayed.*

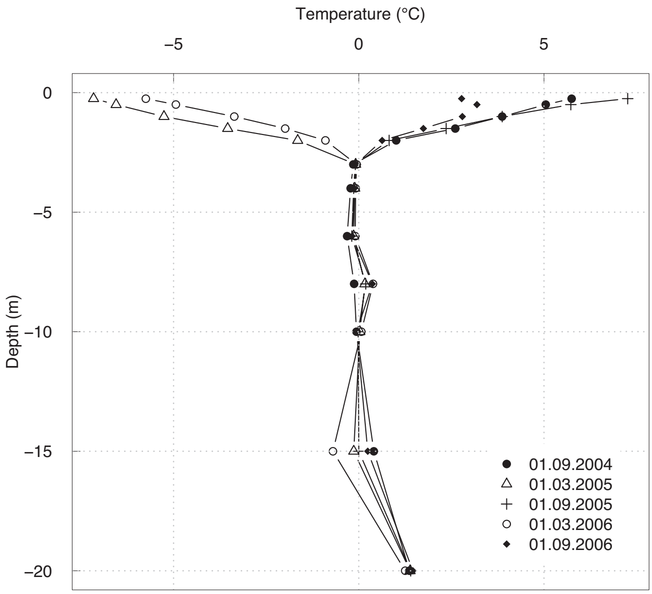

Fig. A.6: *Temperature profiles for Flüela 01/02.*

Gentianes 01/02

Site	
Description	Moraine
Coordinates	589450/103650
Elevation (m a.s.l.)	2890
Slope angle (°)	Flat
Slope aspect	–
Morphology	Lateral moraine
Lithology	Gneiss
MAAT/Precipitation	–1.5 °C / 1700 mm
Vegetation	No vegetation
Borehole	
Drilling date	10.2002
Depth (m)	20
Chain length (m)	20
Thermistor depths (m)	0.5, 1.0, 1.5, 2.3, 3.6, 5.09, 7.08, 9.57, 12.56, 20.04
Thermistor type	MADD-T30E
Last calibration	10.2002
Responsible	IGUL, C. Lambiel
Other measurements	DC resistivity soundings, movements (GPS)
Comments	–
Available data	Since 2002

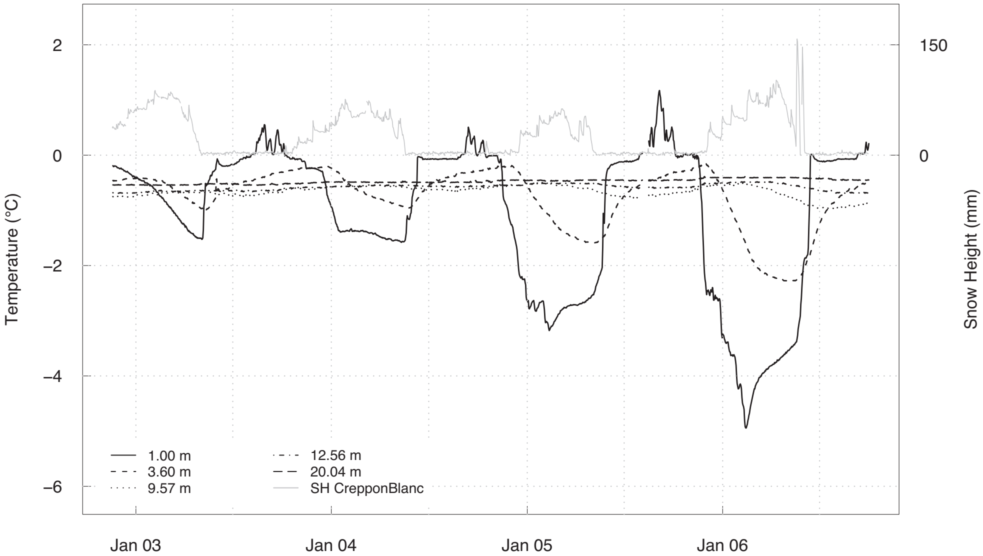

Fig. A.7: *Temperature-time-plot of the borehole Gentianes 01/02 for the thermistors at 1.0, 3.6, 9.57, 12.56, and 20.04 m depth. Additionally, the snow height at Creppon Blanc is displayed.*

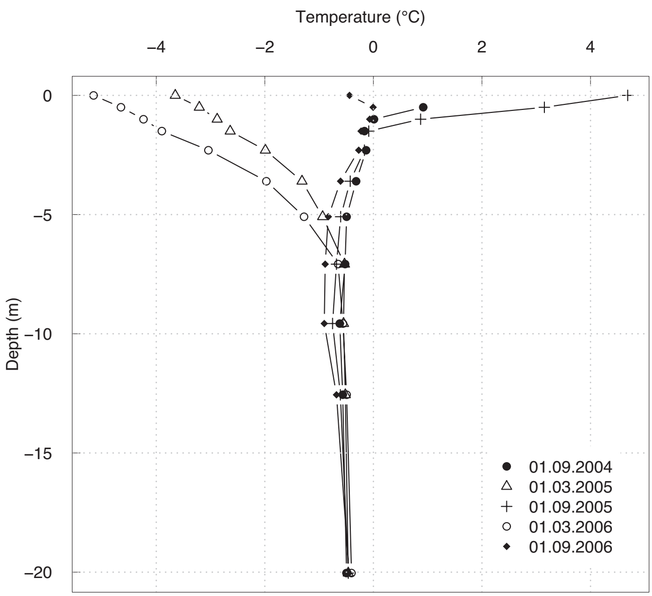

Fig. A.8: *Temperature profiles for Gentianes 01/02.*

Jungfraujoch N/95 and S/95

Site	
Description	North/South face of Jungfrau Ostgrat
Coordinates	N: 641000/155120, S: 640990/155050
Elevation (m a.s.l.)	N: 3590, S: 3580
Slope angle (°)	N: ca. 55°, S: ca. 50°
Slope aspect	N: ca. 5° E, S: ca. 135° E
Morphology	Rock wall
Lithology	Gneiss
MAAT	–7.9 °C
Vegetation	No vegetation
Borehole	
Drilling date	1995
Depth (m)	N: 21, S: 20
Chain length (m)	N: 21, S: 20
Thermistor depth (m)	N: 2.7, 6.7, 9.7, 10.7, 11.7, 15.7, 16.7, 20.2 S: 1.2, 5.2, 8.2, 11.2, 14.2, 16.2, 17.7, 18.7
Thermistor type	NTC Thermistor, Model 111-103-EAJ-H01 (Fenwal Electronics)
Last calibration	1995
Responsible	SLF, M. Phillips
Other measurements	Deformation measurement (1995–2003)
Comments	Boreholes are not vertical; they are drilled outwards from the inner-tunnel. Since 2005, there are problems with lightnings and logger.
Available data	Since 1995

Lapires 01/98

Site	
Description	Val de Nendaz, VS
Coordinates	588070/106080
Elevation (m a.s.l.)	2500
Slope angle (°)	25
Slope aspect	NE
Morphology	Talus slope
Lithology	Gneiss (mainly)
MAAT	0.5 °C
Vegetation	No vegetation
Borehole	
Drilling date	10.1998
Depth (m)	19.6
Chain length (m)	19.6
Thermistor depths (m)	0.7, 1.7, 2.45, 2.8, 3.15, 3.61, 4.03, 4.51, 5.01, 6.7, 11.1, 19.6
Thermistor type	Pt 100
Last calibration	11.1998
Meteostation	
Installation date	11.1998
Sensors	Air temperature, shortwave radiation, reflected shotwave radiation
Responsible	IGUF, R. Delaloye
Other measurements	BTS/GST
Comments	Temperate (warm) permafrost, air circulation through the talus slope
Available data	Since 1998 (with some gaps)

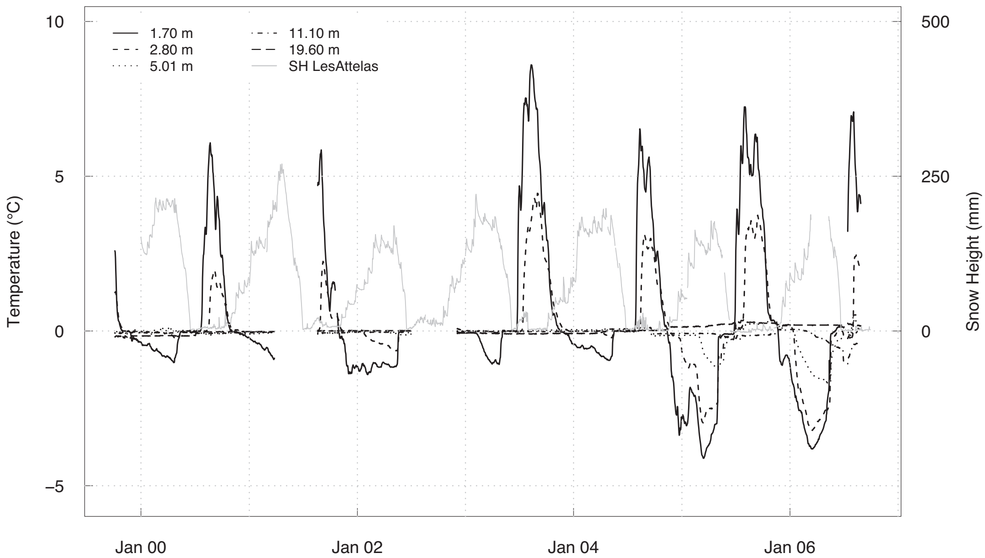

Fig. A.9: *Temperature-time-plot of the borehole Lapires 01/98 for the thermistors at 1.70, 2.80, 5.01, 11.10, and 19.60 m depth. Additionally, the snow height at Les Attelas is displayed.*

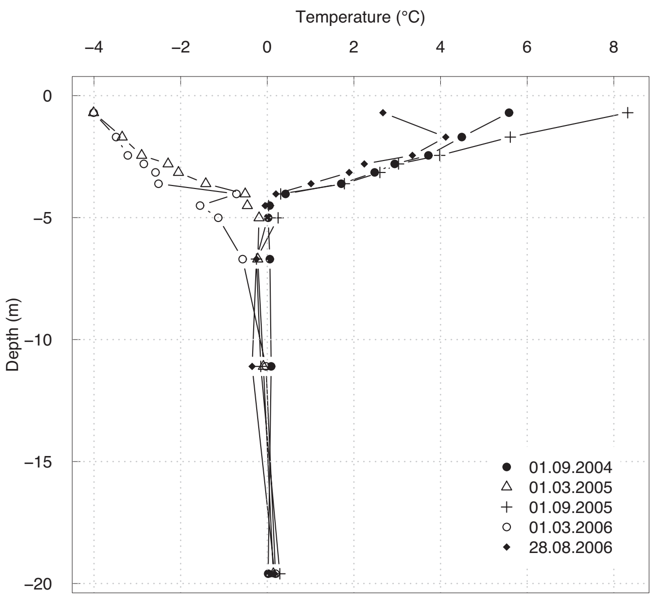

Fig. A.10: *Temperature profiles for Lapires 01/98.*

Muot da Barba Peider 01/96 and 02/96

Site	
Description	Schafberg-Pontresina (Muot da Barba Peider), Upper Engadine, GR
Coordinates	01/96: 791300/152500; 02/96: 791300/152500
Elevation (m a.s.l.)	01/96: 2946; 02/96: 2941
Slope angle (°)	38
Slope aspect	NW
Morphology	Scree slope
Lithology	Gneiss
MAAT/Precipitation	–4.5 °C / 2000 mm
Vegetation	No vegetation
Borehole	
Drilling date	1996
Depth (m)	18
Chain length (m)	17.5
Thermistor depths (m)	0.5, 1.0, 2.0, 3.0, 4.0, 6.0, 8.0, 10.0, 13.5, 17.5
Thermistor type	YSI 46008 + Campbell CR10X 1996
Last calibration	1996
Meteostation	
Installation date	1996
Sensors	Air temperature (UTL), radiation, snow-surface, wind speed/direction
Responsible	SLF, M. Phillips
Other measurements	BTS/GST
Comments	Snow nets at 01/96, no snow nets at 02/96
Available data	Since 1996

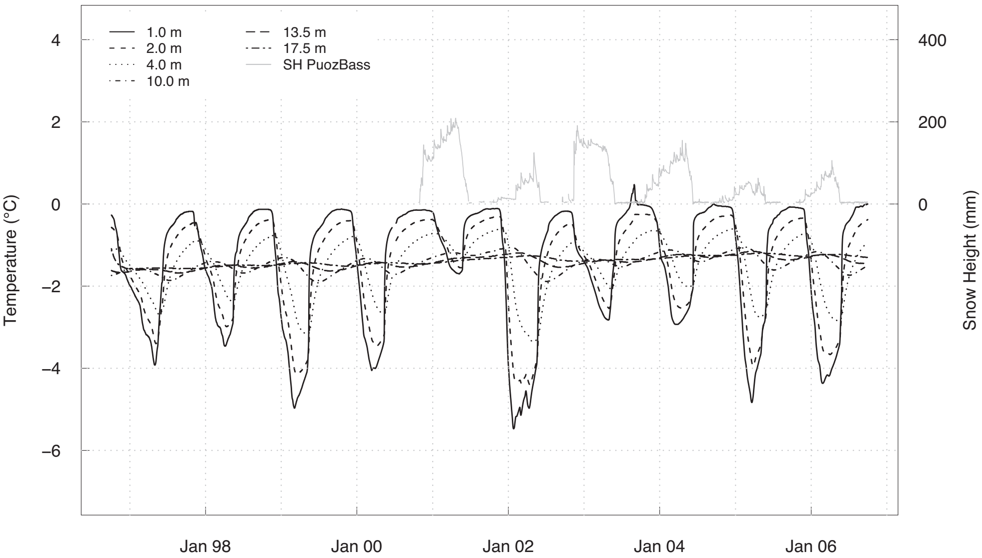

Fig. A.11: *Temperature-time-plot of the borehole Muot da Barba Peider 01/96 for the thermistors at 1.0, 2.0, 4.0, 10.0, 13.5, and 17.5 m depth. Additionally, the snow height at Puoz Bass and Corvatsch is displayed.*

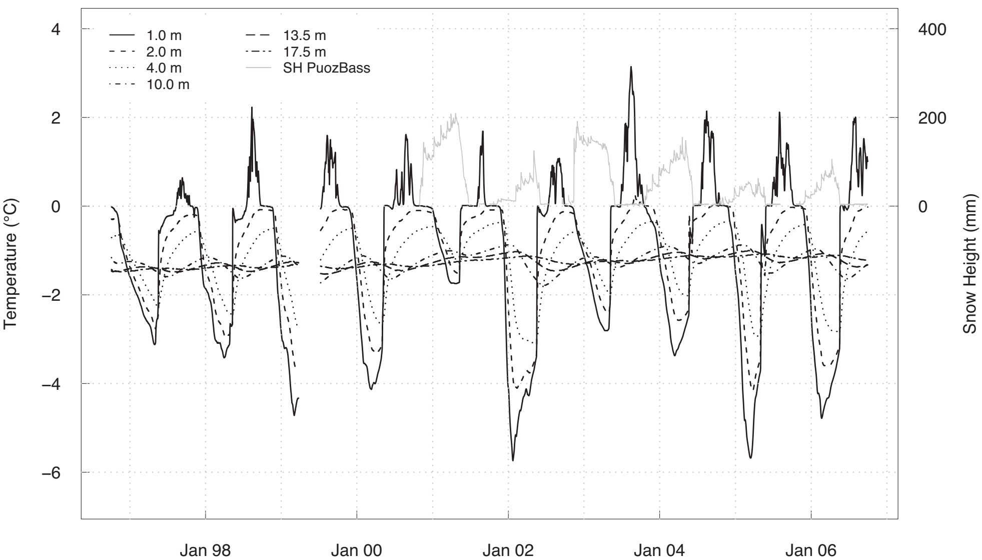

Fig. A.12: *Temperature-time-plot of the borehole Muot da Barba Peider 02/96 for the thermistors at 1.0, 2.0, 4.0, 10.0, 13.5, and 17.5 m depth. Additionally, the snow height at Puoz Bass and Corvatsch is displayed.*

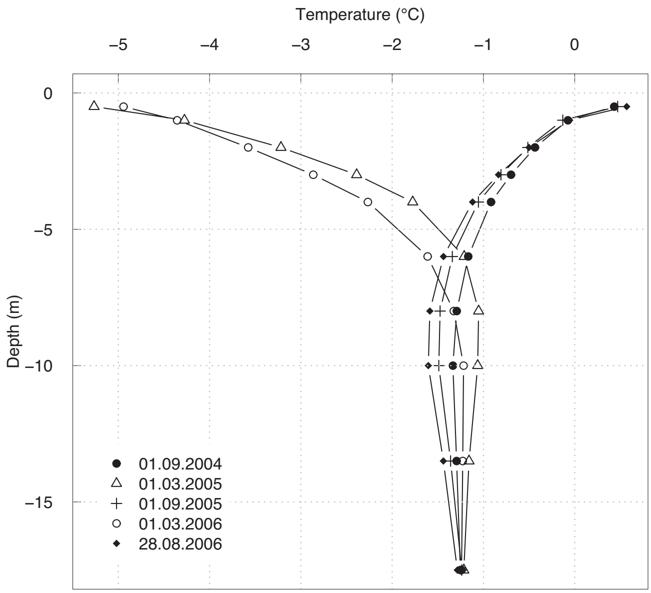

Fig. A.13: Temperature profiles for Muot da Barba Peider 01/96.

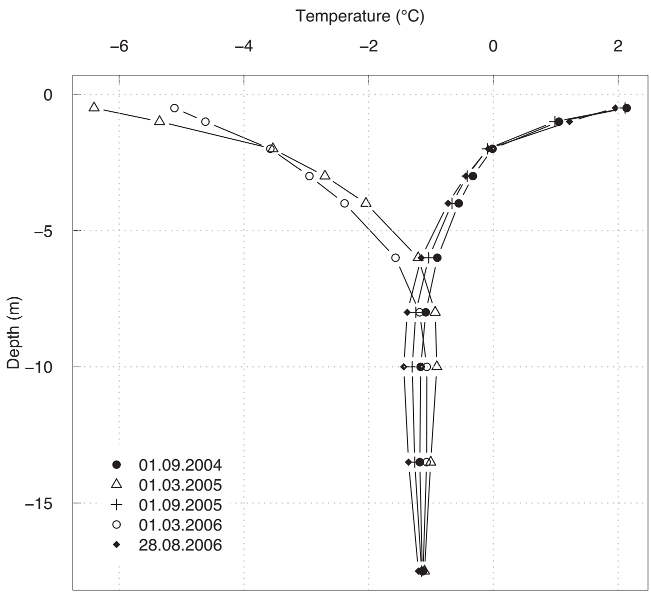

Fig. A.14: Temperature profiles for Muot da Barba Peider 02/96.

Muragl 01/99, 02/99, 03/99, and 04/99

Site	
Description	Active rock glacier in the Muragl Valley with a pronounced curvature in the flow. Approx. 45 min from Muottas Muragl.
Coordinates	01/99: 791025/153726, 02/99: 790989/153687 03/99: 791038/153679, 04/99: 791017/153688
Elevation [m a.s.l.]	01/99: 2536.1, 02/99: 2538.5 03/99: 2558.2, 04/99: 2549.2
Slope angle [°]	01/99: 15°, 02/99: 5°, 03/99: 15°, 04/99: 15°
Slope aspect	01/99: W, 03/99: SW, 04/99: SW
Morphology	Active rockglacier
Lithology	Albit-Muskowit schists
MAAT/Precipitation	–2.2 °C / 2000 mm
Vegetation	No vegetation
Borehole	
Drilling date	May, June 1999
Depth [m]	01/99: 70.2, 02/99: 64.0 03/99: 72.0, 04/99: 71.0
Chain length [m]	01/99: 69.7, 02/99: 59.7 03/99: 69.6, 04/99: 69.6
Thermistor depths [m]	01/99: 0.0, 0.2, 0.8, 1.4, 2.0, 3.0, 4.0, 5.0, 7.0, 9.0, 11.0, 14.0, 19.0, 24.0, 29.0, 39.0, 54.0, 69.0 02/99: 0.0, 0.1, 0.5, 0.9, 1.3, 1.7, 2.2, 2.7, 3.7, 4.7, 5.7, 7.7, 9.7, 11.7, 13.7, 15.7, 19.7, 24.7, 29.7, 34.7, 39.7, 59.7, 59.7 03/99: 0.0, 0.4, 0.8, 1.2, 1.6, 2.1, 2.6, 3.6, 4.6, 5.6, 7.6, 9.6, 11.6, 13.6, 15.6, 17.6, 19.6, 24.6, 29.6, 34.6, 39.6, 49.6, 59.6, 69.6 04/99: 0.0, 0.4, 0.8, 1.2, 1.6, 2.1, 2.6, 3.6, 4.6, 5.6, 7.6, 9.6, 11.6, 13.6, 15.6, 19.6, 24.6, 29.6, 34.6, 39.6, 59.6, 69.6
Thermistor type	YSI 44006
Last calibration	05.999
Responsible	IGT-ETH, L. Arenson, S.M. Springman
Other measurements	BTS/GST
Comments	–
Available data	01/99: 10.99–04.00, 09.02–, 02/99: 11.00– 03/99: 10.99–04.00, 09.02–, 04/99: 10.99–04.00, 09.02–

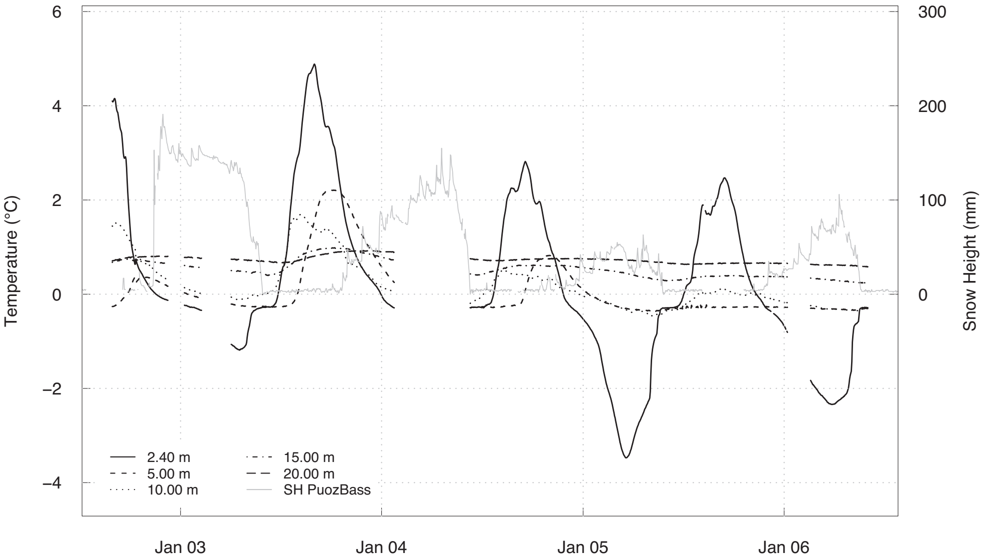

Fig. A.15: *Temperature-time-plot of the borehole Muragl 01/99 for the thermistors at 2.4, 5.0, 10.0, 15.0, and 20.0 m depth. Additionally, the snow height at Puoz Bass is displayed.*

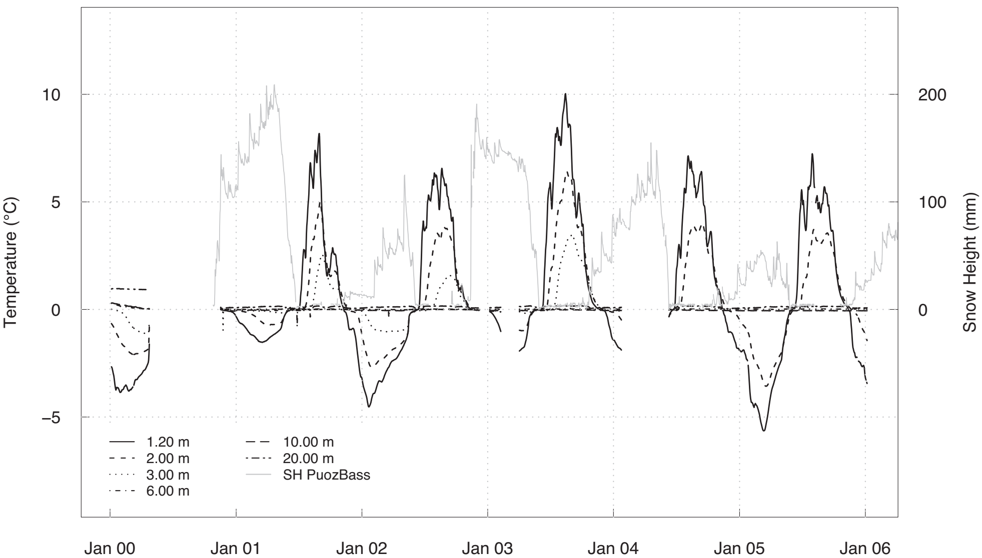

Fig. A.16: *Temperature-time-plot of the borehole Muragl 02/99 for the thermistors at 1.2, 2.0, 3.0, 6.0, 10.0, and 20.0 m depth. Additionally, the snow height at Puoz Bass is displayed.*

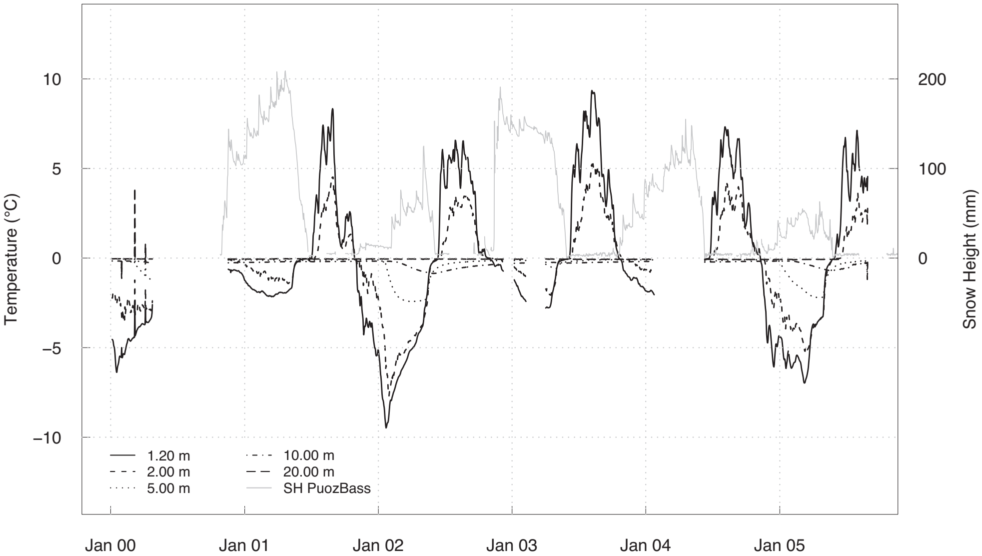

Fig. A.17: *Temperature-time-plot of the borehole Muragl 03/99 for the thermistors at 1.2, 2.0, 5.0, 10.0, and 20.0 m depth. Additionally, the snow height at Puoz Bass is displayed.*

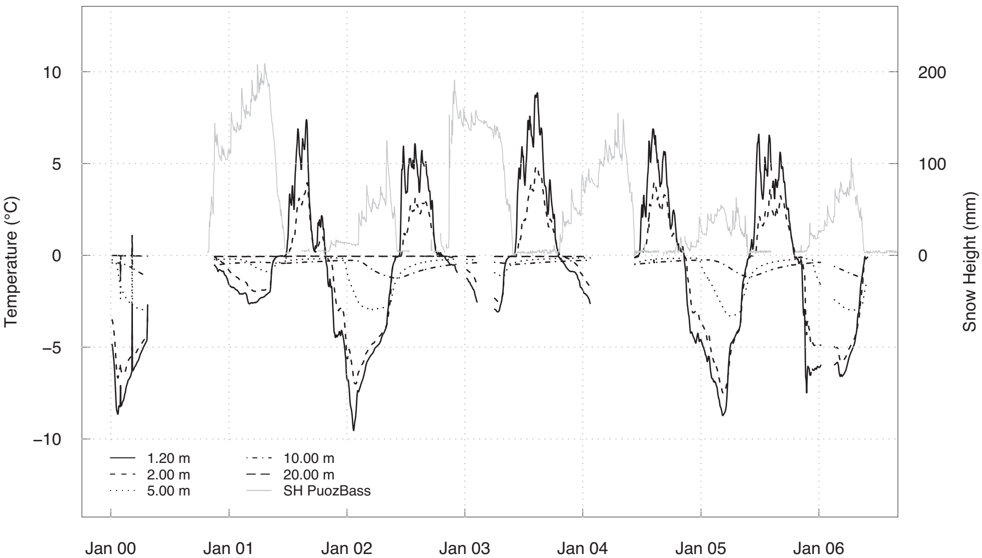

Fig. A.18: *Temperature-time-plot of the borehole Muragl 04/99 for the thermistors at 1.2, 2.0, 5.0, 10.0, and 20.0 m depth. Additionally, the snow height at Puoz Bass is displayed.*

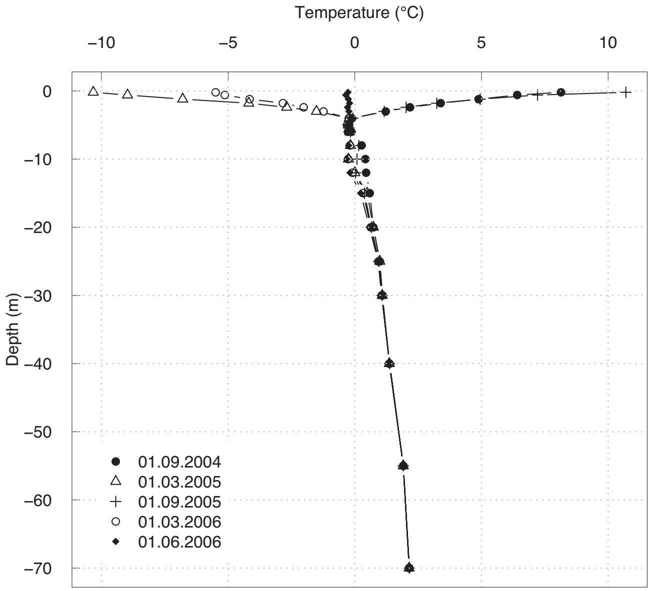

Fig. A.19: *Temperature profiles for Muragl 01/99.*

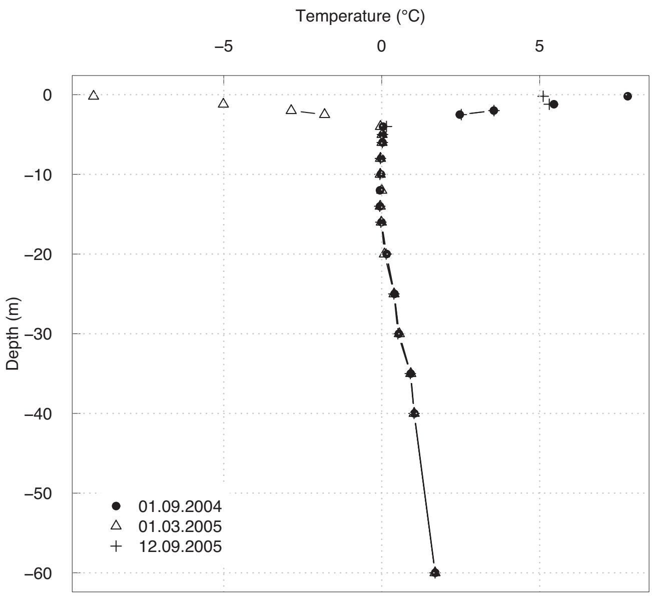

Fig. A.20: *Temperature profiles for Muragl 02/99.*

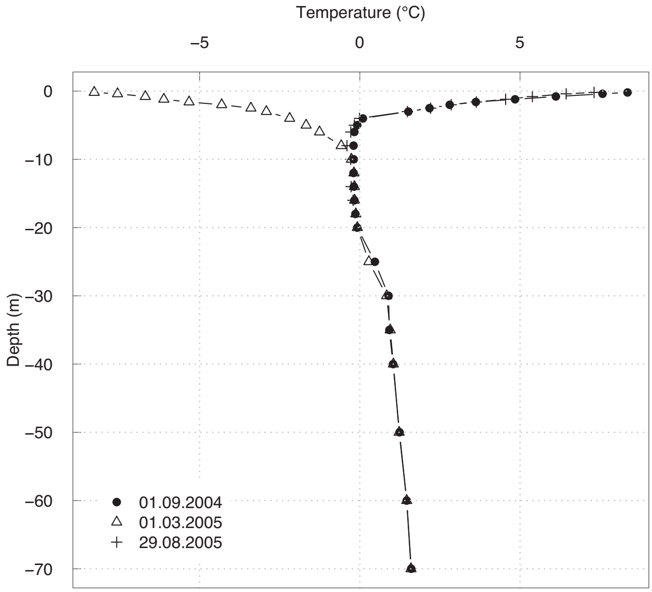

Fig. A.21: Temperature profiles for Muragl 03/99.

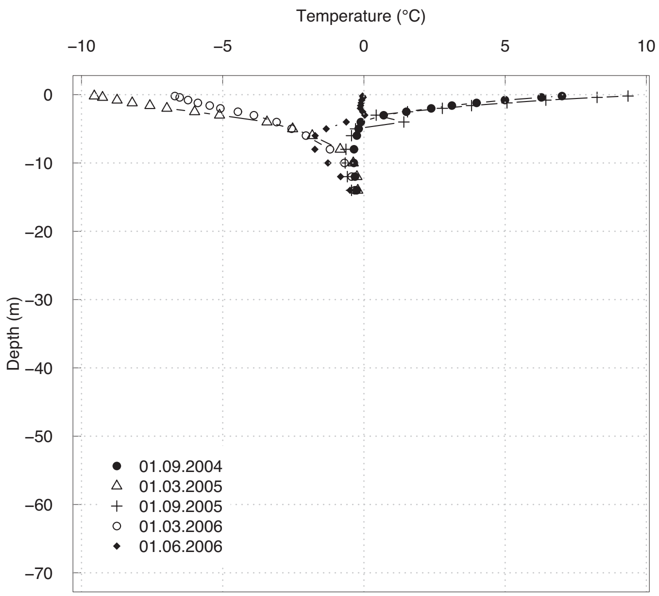

Fig. A.22: Temperature profiles for Muragl 04/99.

Murtèl-Corvatsch 02/87

Site	
Description	Active rock glacier south-west of the cable car station Murtèl
Coordinates	783160/144720
Elevation (m a.s.l.)	2670
Slope angle (°)	10°
Slope aspect	NNW
Morphology	Rock glacier
Lithology	Crystalline rock of the Corvatsch nappe: granodiorit, schists
MAAT/Precipitation	–3 °C / 2000 mm
Vegetation	No vegetation
Borehole	
Drilling date	06.1987
Depth (m)	62.0
Chain length (m)	58.0
Thermistor depths (m)	0.6, 1.6, 2.6, 3.6, 4.6, 5.6, 6.6, 7.6, 8.6, 9.6, 10.6, 11.6, 12.6, 13.6, 14.6, 15.6, 16.6, 17.6, 18.6, 19.6, 20.6, 21.6, 23.6, 24.6, 25.6, 26.6, 27.6, 30.0, 33.0, 36.0, 39.0, 42.0, 45.0, 46.0, 47.0, 48.0, 49.0, 50.0, 51.0, 52.0, 53.0, 53.9, 54.9, 55.9, 56.9, 58.0
Thermistor type	2/87: YSI 44006, Fernwall UUA 41J1
Last calibration	fix installed
Meteostation	
Installation date	1.1997
Sensors	Air and surface temperature, relative humidity, net radiation, snow-depth, wind speed/direction
Responsible	GIUZ, M. Hoelzle
Other measurements	BTS/GST
Comments	Air circulation through talus slope
Available data	Since 1987 (with some gaps)

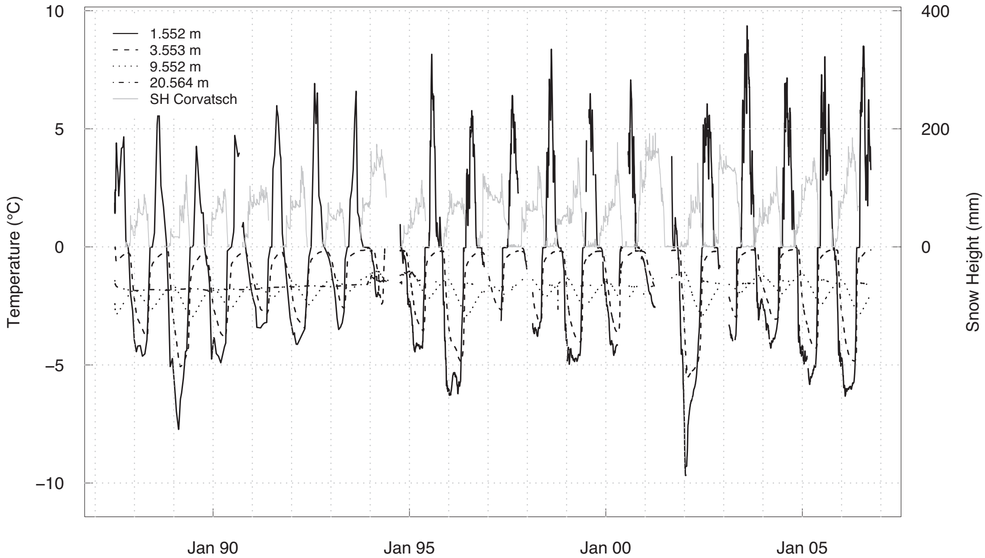

Fig. A.23: *Temperature-time-plot of the borehole Corvatsch 02/87 for the thermistors at 1.55, 3.55, 9.55, and 20.56 m depth. Additionally, the snow height at Corvatsch is displayed.*

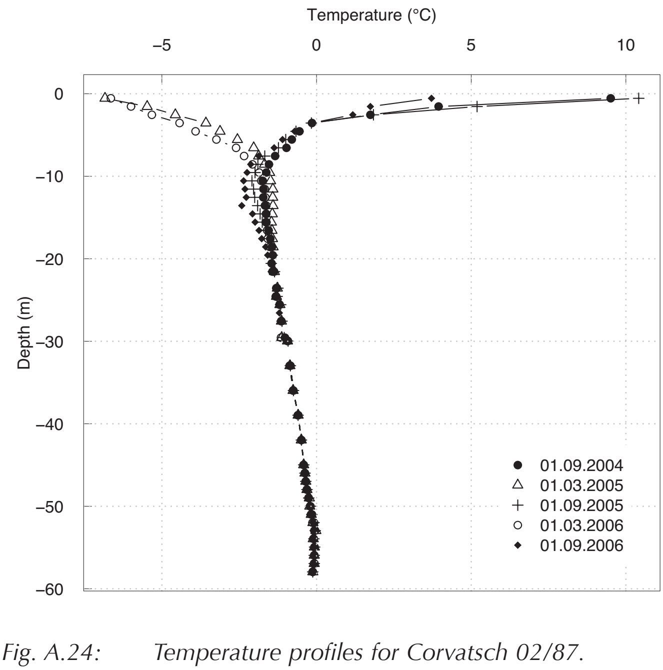

Fig. A.24: *Temperature profiles for Corvatsch 02/87.*

Schafberg-Pontresina 01/90 und 02/90

Site

Description	Schafberg-Pontresina (Muot da Barba Peider), Upper Engadine, GR
Coordinates	1/90: 791000/152500, 2/90: 790750/152775
Elevation (m a.s.l.)	1/90: 2755, 2/90: 2735
Slope angle (°)	Flat
Slope aspect	Flat
Morphology	Rockglacier
Lithology	Gneiss
MAAT/Precipitation	–3.5 °C / 2000 mm
Vegetation	No vegetation

Borehole

Drilling date	1990
Depth (m)	01/90: 67.0, 02/90: 37.0
Chain length (m)	01/90: 18.0, 02/90: 25.2
Thermistor depths (m)	02/90: 0.0, 1.2, 3.2, 5.2, 7.2, 9.2, 13.2, 17.2, 21.2, 25.2
Thermistor type	02/90: YSI 46006 + Campbell CR10X
Last calibration	02/90: 1997

Meteostation

Installation date	Planned for summer 2004
Sensors	Air temperature, relative humidity, net radiation, snow depth/surface/temperature, wind speed/direction

Responsible	SLF, M. Phillips
Other measurements	BTS/GST
Comments	Borehole 02/90 sheared off in 2000 at 28 m
Available data	01/90: since 2005, 02/90: since 1997

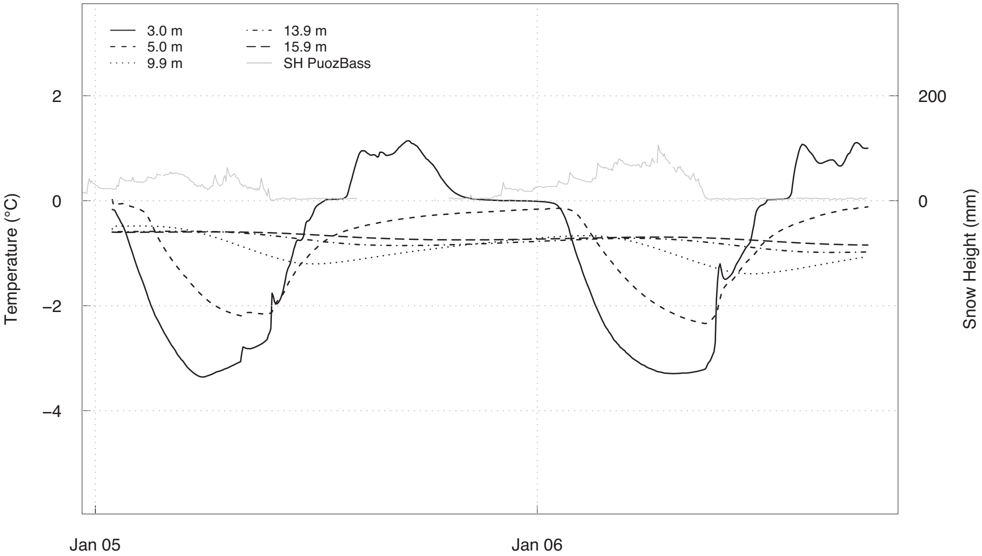

Fig. A.25: *Temperature-time-plot of the borehole Schafberg-Pontresina 01/90 for the thermistors at 3.0, 5.0, 9.9, 13.9, and 15.9 m depth. Additionally, the snow height at Puoz Bass is displayed.*

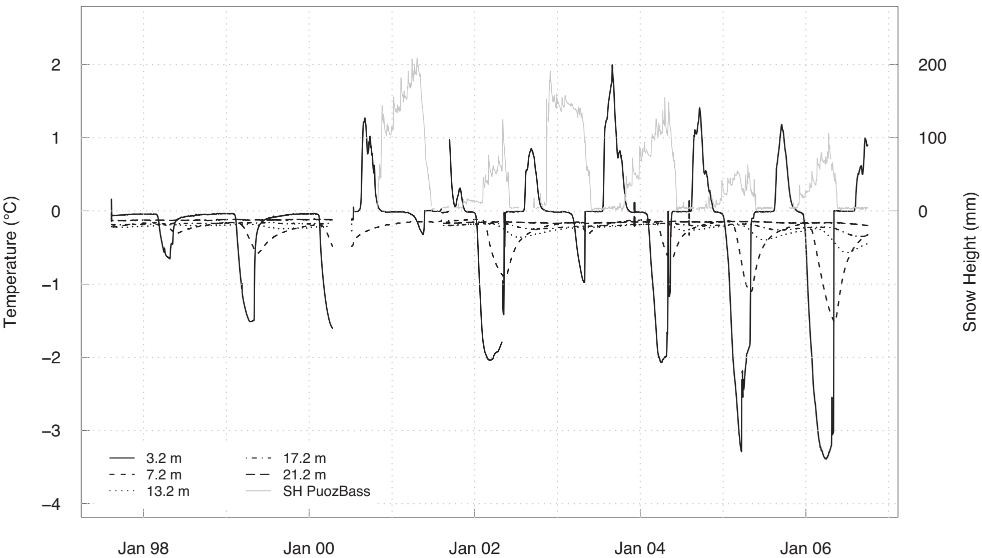

Fig. A.26: *Temperature-time-plot of the borehole Schafberg-Pontresina 02/90 for the thermistors at 3.2, 7.2, 13.2, 17.2, and 21.2 m depth. Additionally, the snow height at Puoz Bass is displayed.*

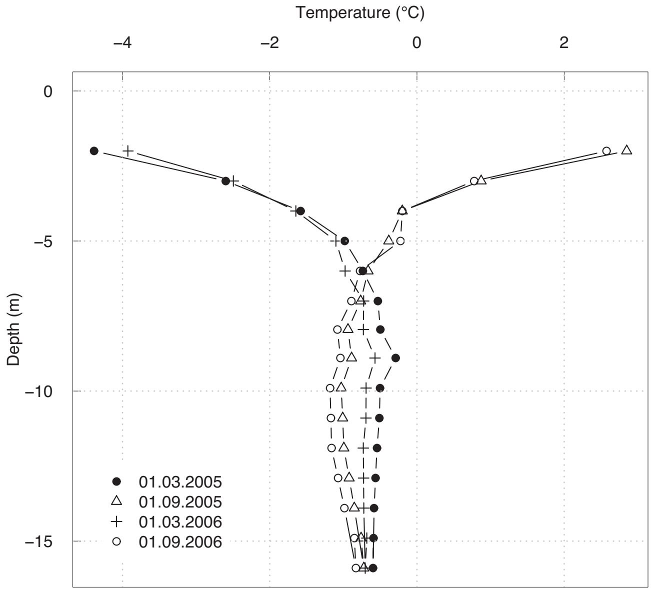

Fig. A.27: *Temperature profiles for Schafberg 01/90.*

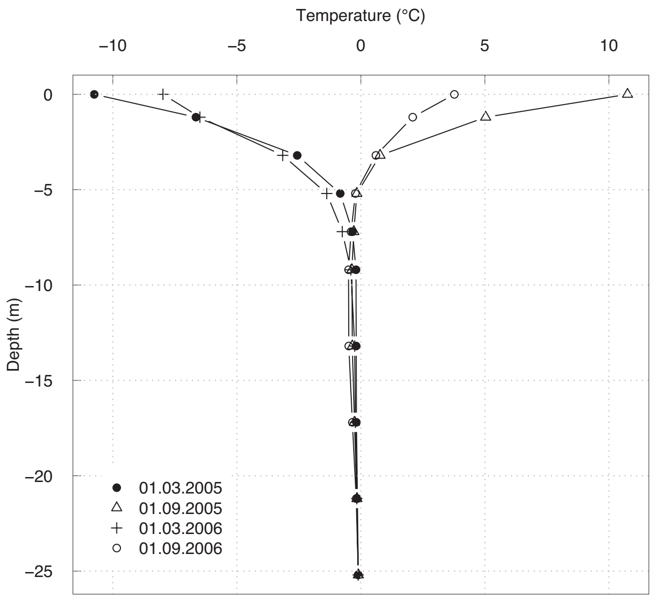

Fig. A.28: *Temperature profiles for Schafberg 02/90.*

Schilthorn 51/98, 50/00, and 52/00

Site	
Description	North-east face of Schilthorn, Lauterbrunnental, BE
Coordinates	51/98: 630365/156410, 50/00: 630350/156410, 52/00:630350/156410
Elevation (m a.s.l.)	51/98: 2909, 50/00: 2910, 52/00: 2910
Slope angle (°)	30
Slope aspect	NE
Morphology	Slope beneath summit
Lithology	Limestone schists
MAAT/Precipitation	–4.3 °C / 2700 mm
Vegetation	No vegetation
Borehole	
Drilling date	51/98: 14.10.1998, 50/00 and 52/00: 8.2000
Depth (m)	51/98: 14 m , 50/00: 101.0 m, 52/00: 100.0 m
Chain length (m)	51/98: 13.7 m, 50/00: 100.0 m, 52/00: 100.0 (installed down to 92.0)
Thermistor depth (m)	51/98: 0.2, 0.4, 0.8, 1.2, 1.6, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 7.0, 9.0, 10.0, 11.0, 13.0, 13.7 50/00: 0.2, 0.4, 0.8, 1.2, 1.6, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 7.0, 9.0, 10.0, 11.0, 13.0, 15.0, 20.0, 25.0, 30.0, 40.0, 50.0, 60.0, 70.0, 80.0, 85.0, 90.0, 95.0, 97.5, 100.0 52/00: 0.0, 1.0, 2.0, 3.0, 5.0, 7.0, 12.0, 17.0, 22.0, 32.0, 42.0, 52.0, 62.0, 72.0, 77.0, 82.0, 87.0, 89.5, 92.0
Thermistor type	NTC-YSI 440006
Last calibration	51/98: 1998, 50/00: 1999, 52/00: 1999
Meteostation	
Installation date	10.1998
Sensors	Air temperature, relative humidity, net radiation, snow-depth, wind speed, wind direction
Responsible	GIUZ, M. Hoelzle
Other measurements	BTS/GST, energy balance
Comments	Temperate (warm) permafrost
Available data	Since 1998 (with some gaps)

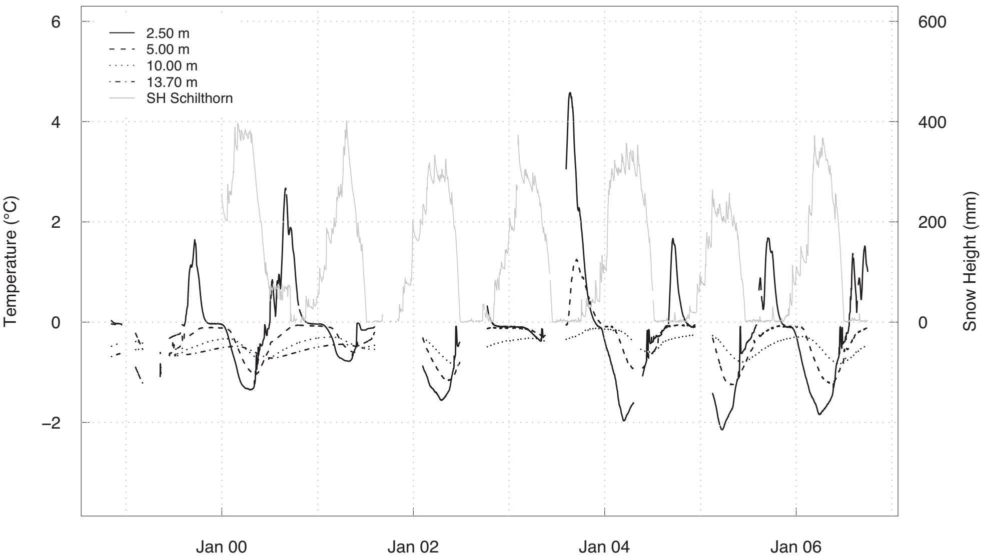

Fig. A.29: *Temperature-time-plot of the borehole Schilthorn 51/98 for the thermistors at 4.0, 5.0, 10.0, and 13.7 m depth. Additionally, the snow height on Schilthorn is displayed.*

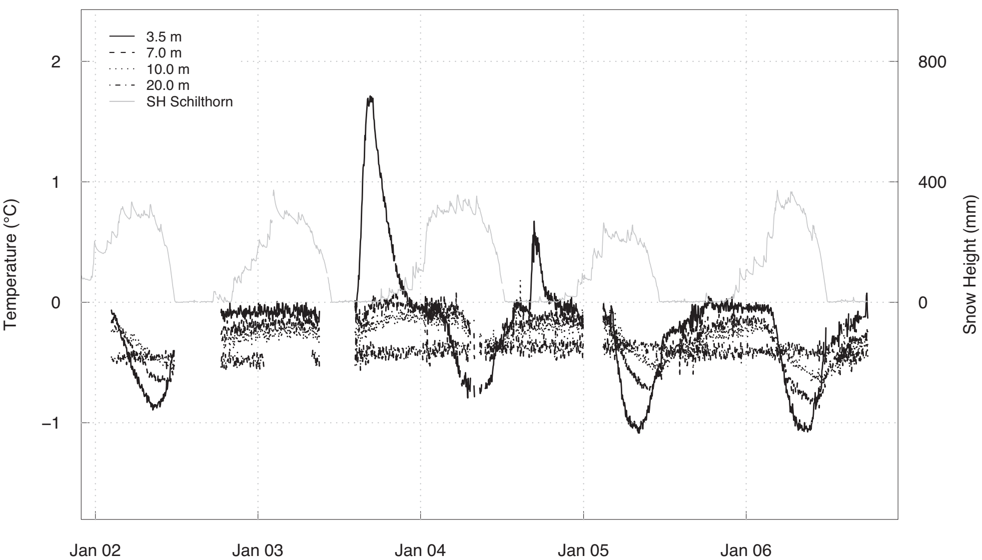

Fig. A.30: *Temperature-time-plot of the borehole Schilthorn 50/00 for the thermistors at 3.0, 7.0, 10.0, and 20.0 m depth. Additionally, the snow height on Schilthorn is displayed.*

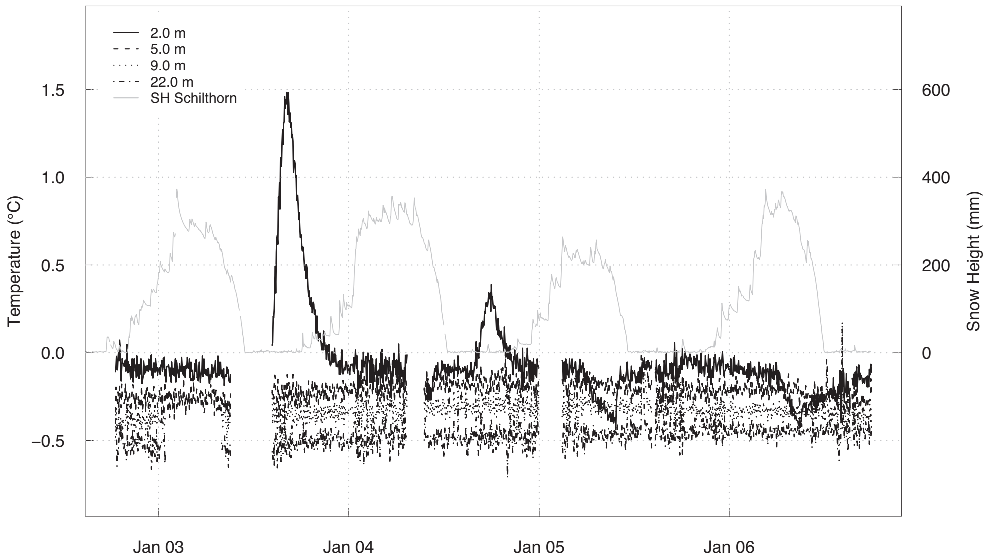

Fig. A.31 *Temperature-time-plot of the borehole Schilthorn 52/00 for the thermistors at 2.0, 5.0, 9.0, and 22.0 m depth. Additionally, the snow height on Schilthorn is displayed.*

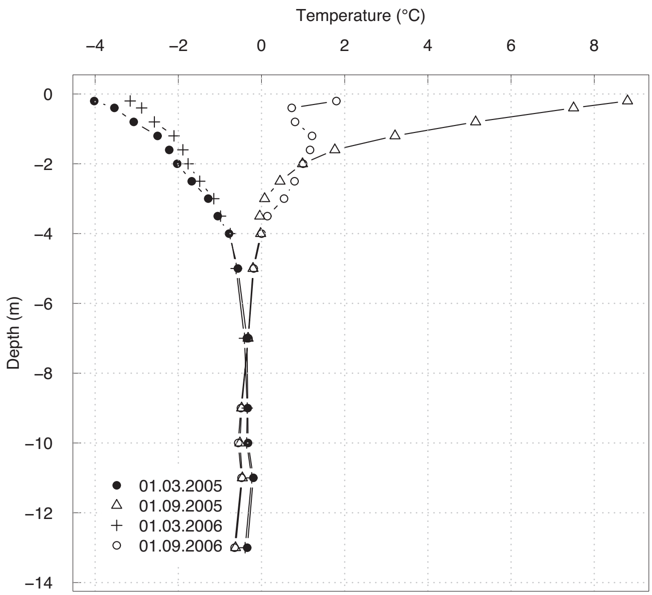

Fig. A.32: *Temperature profiles for Schilthorn 51/98.*

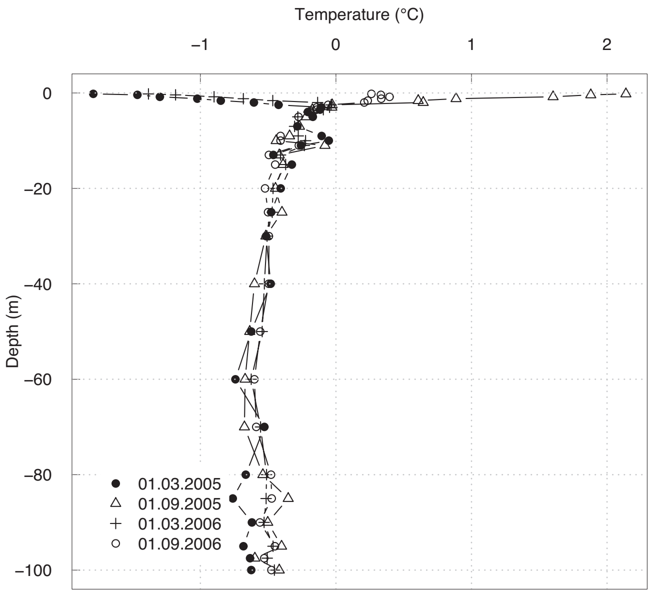

Fig. A.33: Temperature profiles for Schilthorn 50/00.

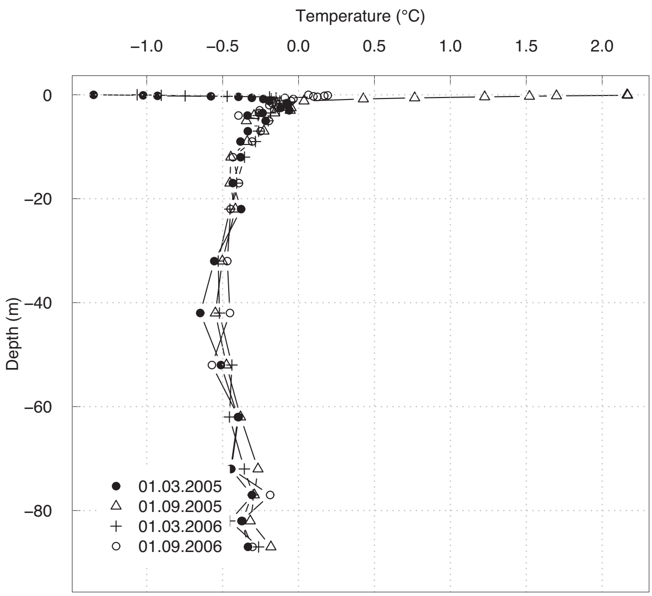

Fig. A.34: Temperature profiles for Schilthorn 52/00.

Stockhorn 60/00 and 61/00

Site	
Description	Stockhorn Plateau, Gornergrat, Matter Valley, VS
Coordinates	60/00: 629878/92876; 61/00: 629867/92850
Elevation (m a.s.l.)	3410
Slope angle (°)	8
Slope aspect	S
Morphology	Plateau on crest
Lithology	Albit-Muskowit schists
MAAT/Precipitation	–5.5 °C / 1500 mm
Vegetation	No vegetation
Borehole	
Drilling date	August 2000
Depth (m)	60/00: 100; 61/00: 31
Chain length (m)	60/00: 100; 61/00: 17
Thermistor depths (m)	PACE standard
Thermistor type	NTC-YSI 440006
Last calibration	August 2000
Meteostation	
Installation date	6.2002
Sensors	Air temperature, relative humidity, net radiation, snow-depth, wind speed/ direction
Responsible	GIUZ, M. Hoelze and S. Gruber; Univ. Giessen, L. King
Other measurements	BTS/GST
Comments	–
Available data	Since 2000

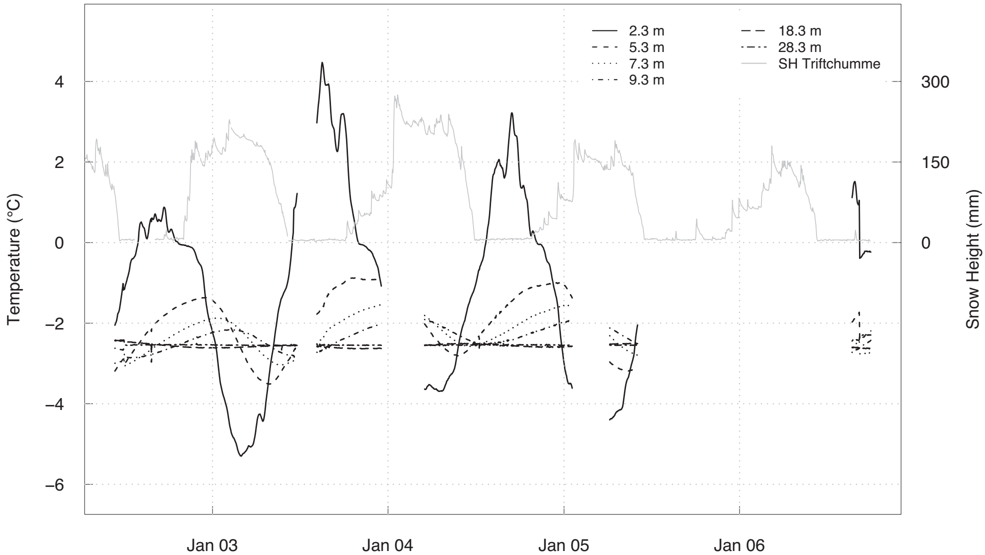

Fig. A.35: *Temperature-time-plot of the borehole Stockhorn 60/00 for the thermistors at 2.3, 5.3, 7.3, 9.3, 18.3, and 28.3 m depth. Additionally, the snow height at Zermatt Triftchumme is displayed.*

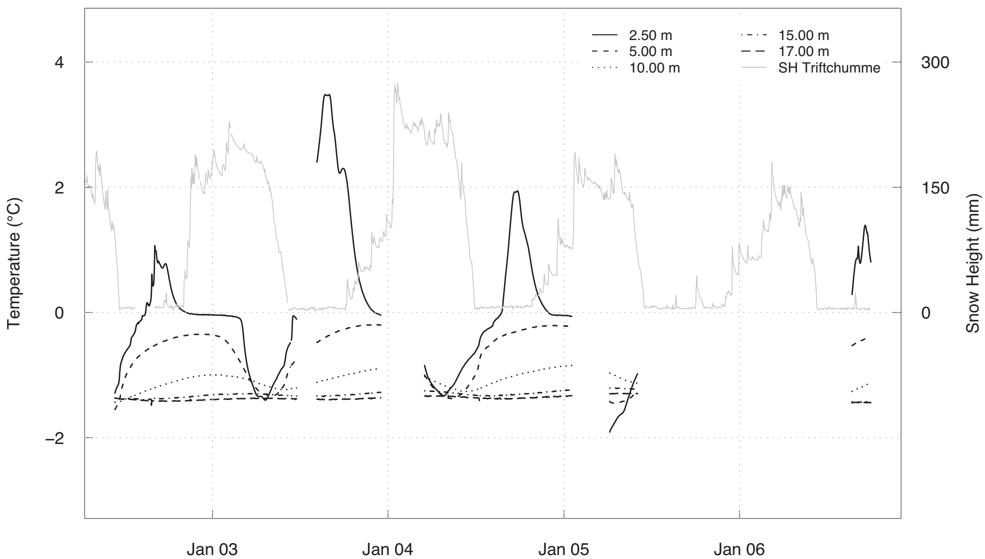

Fig. A.36: *Temperature-time-plot of the borehole Stockhorn 61/00 for the thermistors at 2.5, 5.0, 10.0, 15.0, and 17.0 m depth. Additionally, the snow height at Zermatt Triftchumme is displayed.*

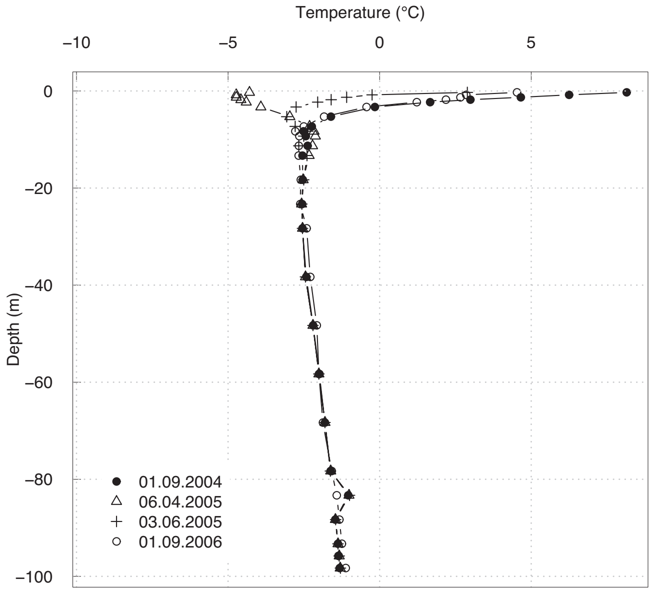

Fig. A.37: *Temperature profiles for Stockhorn 60/00.*

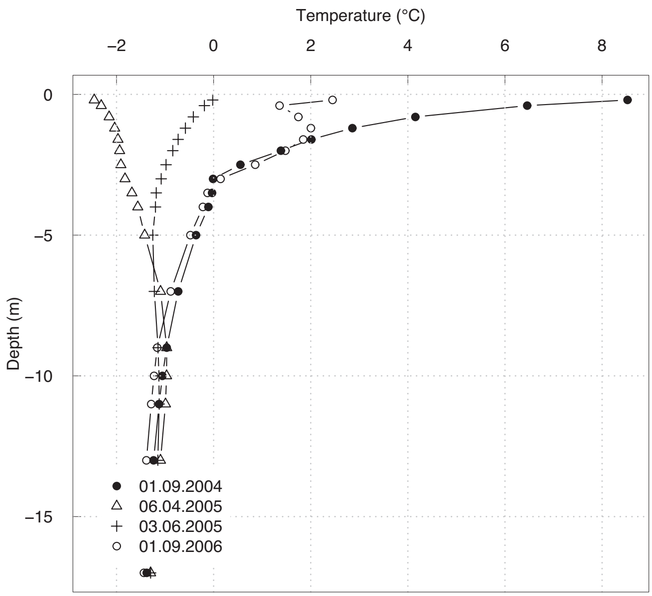

Fig. A.38: *Temperature profiles for Stockhorn 61/00.*

Tsaté 01/04

Site	
Description	Bedrock
Coordinates	608500/106400
Elevation (m a.s.l.)	3040
Slope angle [°]	35
Slope aspect	W
Morphology	Rock slope
Lithology	Calc-schist
MAAT/Precipitation	–1.5 °C / 1700 mm
Vegetation	No vegetation
Borehole	
Drilling date	08.2004
Depth (m)	20
Chain length (m)	19.5
Thermistor depths (m)	0.5, 1.0, 1.5, 2.3, 3.5, 5.0, 7.0, 9.5, 13.0, 19.5
Thermistor type	MADD-T30E
Last calibration	–
Responsible	IGUL, C. Lambiel
Other measurements	–
Comments	–
Available data	Since 2004

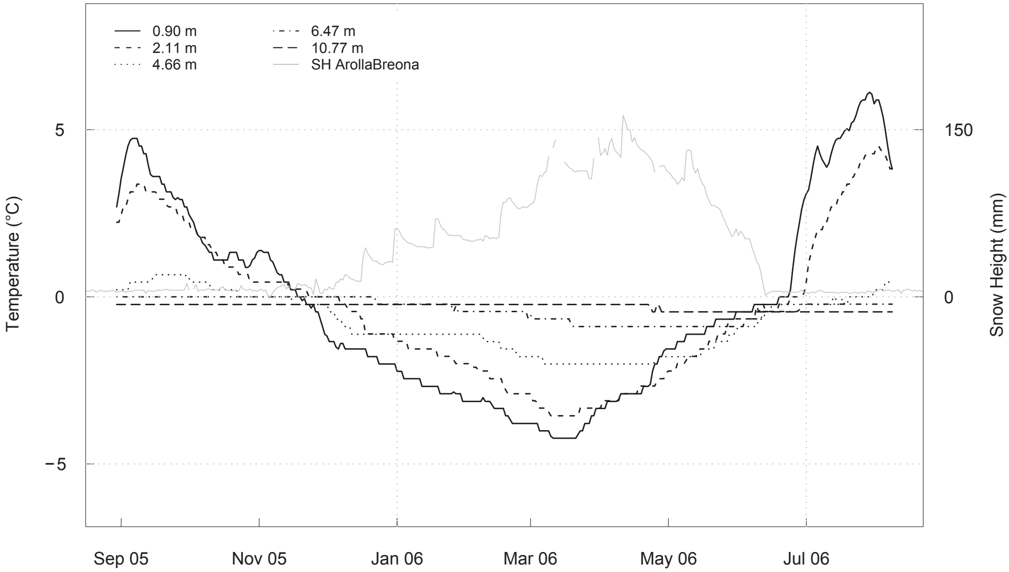

Fig. A.39: *Temperature-time-plot of the borehole Tsaté 01/04 for the thermistors at 3.5, 7.0, 9.5, and 19.0 m depth. Additionally, the snow height at Arolla Breona is displayed.*

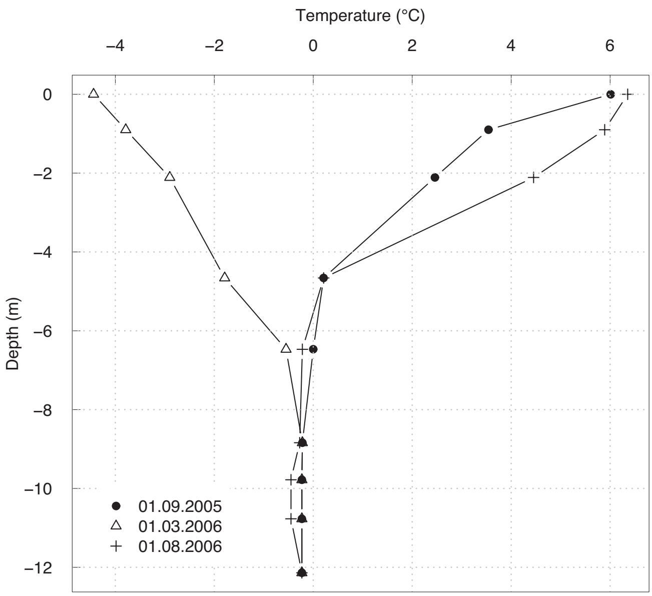

Fig. A.40: *Temperature profile for Tsaté 01/04.*