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Swiss Snow, Ice and Permafrost Society + Swiss Geomorphological Society

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6.1

Long term point observations of seasonal mass balance: a key to understanding 20th century climate change

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Point observations of glacier surface mass balance at fixed locations directly reflect climatic variations and are not biased by uncertain spatial interpolation of mass balance or the change in glacier surface area. Thus, they are considered to be the best indicator for changes in the climatic forcing on glaciers (Vincent and others, 2004; Ohmura and others, 2007). Four long term time series of seasonal mass balance observations (Fig. 1) at fixed locations have been compiled for two stakes on Claridenfirn and one stake on Grosser Aletschgletscher and Silvrettagletscher, Switzerland, all starting in 1914 (Huss and Bauder, in press). These data represent the longest series of direct mass balance measurements worldwide.

Using a mass balance model based on the temperature-index approach, the field observations are corrected for varying dates, inconsistency, systematic errors and data gaps. The resulting homogenized continuous 93-year time series from the three glaciers cover most of the 20th century and enable to investigate temporal, regional and altitudinal variability of mass balance and fluctuations in the climatic forcing on glaciers.

Long term variations in mass balance are mainly driven by changes in summer ablation. Three stakes (Clariden, Silvretta) located near the equilibrium line display significantly lower summer balances in the mid 1960s to mid 1980s, whereas the high altitude site (Aletsch) shows opposite trends. Two periods of enhanced climatic forcing are detected, 1943-1953 and 1987-2007. At all stakes the energy consumed for melt was higher in the 1940s in spite of lower air temperatures than during the last two decades.

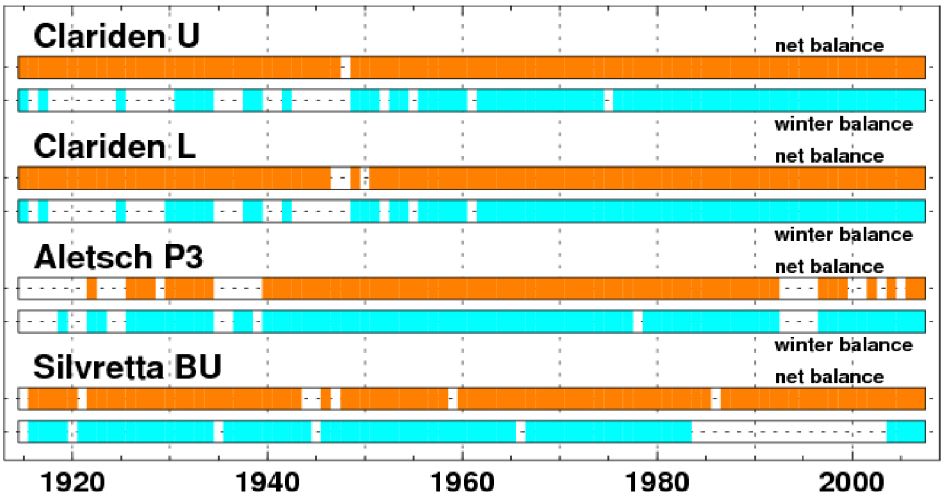

Figure 1. Seasonal observations of point based net and winter balance since 1914 from four sites in the Swiss Alps.

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6.2

Towards a first assessment of the permafrost distribution in the French Alps

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In mountain regions, permafrost is important for the geomorphology of high altitudes areas as well for the water resources of inhabited watersheds. Under the present Global Warming, the possible degradation of permafrost during the coming decades could hence provoke various kind of slope instability and change drastically the hydrological functioning (Kääb et al., 2006). A better understanding of the distribution of the permafrost is therefore a necessary prerequisite for further analysis and mitigation of those hazards.
As permafrost is in most cases invisible and, though covering large areas, its distribution is largely unknown. Extensive permafrost "mapping" can be approached only through either empirical, statistical or physically based modelling (Riseborough et al., 2008). Permafrost maps have been produced this way for the Swiss Alps.
As no such map existed yet for the French Alps, this paper thus intends to present an overview of the main available datasets on the presence of permafrost, in rockfaces as well within debris accumulations: inventories of geomorphological indicators (rockglaciers and other creeping landforms related to the presence of ground ice) and in-situ measurements (BTS, geophysical soundings ...).
Among various types of available models, a statistico-empirical one has been set up: it is based on the relation between the two most important topoclimatic controls (solar radiation and air temperature) of the rockglaciers presence. This relation was computed on a lithologically, geomorphologically and climatically homogeneous small massif (Combeynot Massif, ≈ 45° N, 40km) which presents numerous rockglaciers in various topoclimatic contexts (Bodin, 2007). Two versions of the model, one for the root of rockglaciers, one for their frontal part, have been combined to assess the potential presence of permafrost in the entire French Alps.
Two validation procedures have been performed using independent rockglaciers inventories: one in the Mercantour Massif (lat. ≈ 44° N), one in the Vanoise Massif (lat. ≈ 45.5° N). The comparison between training set and validation set shows a good correspondence of the altitude and aspect of the actual rockglaciers and of the modelled front and root areas. Those first results are thus encouraging as they already provide to public and to decision-makers usable new information about permafrost presence in their territory. At fine scales (lower than the watershed), more investigations are nevertheless necessary to detect and characterise precisely the permafrost, either in debris accumulation or in rock-face.

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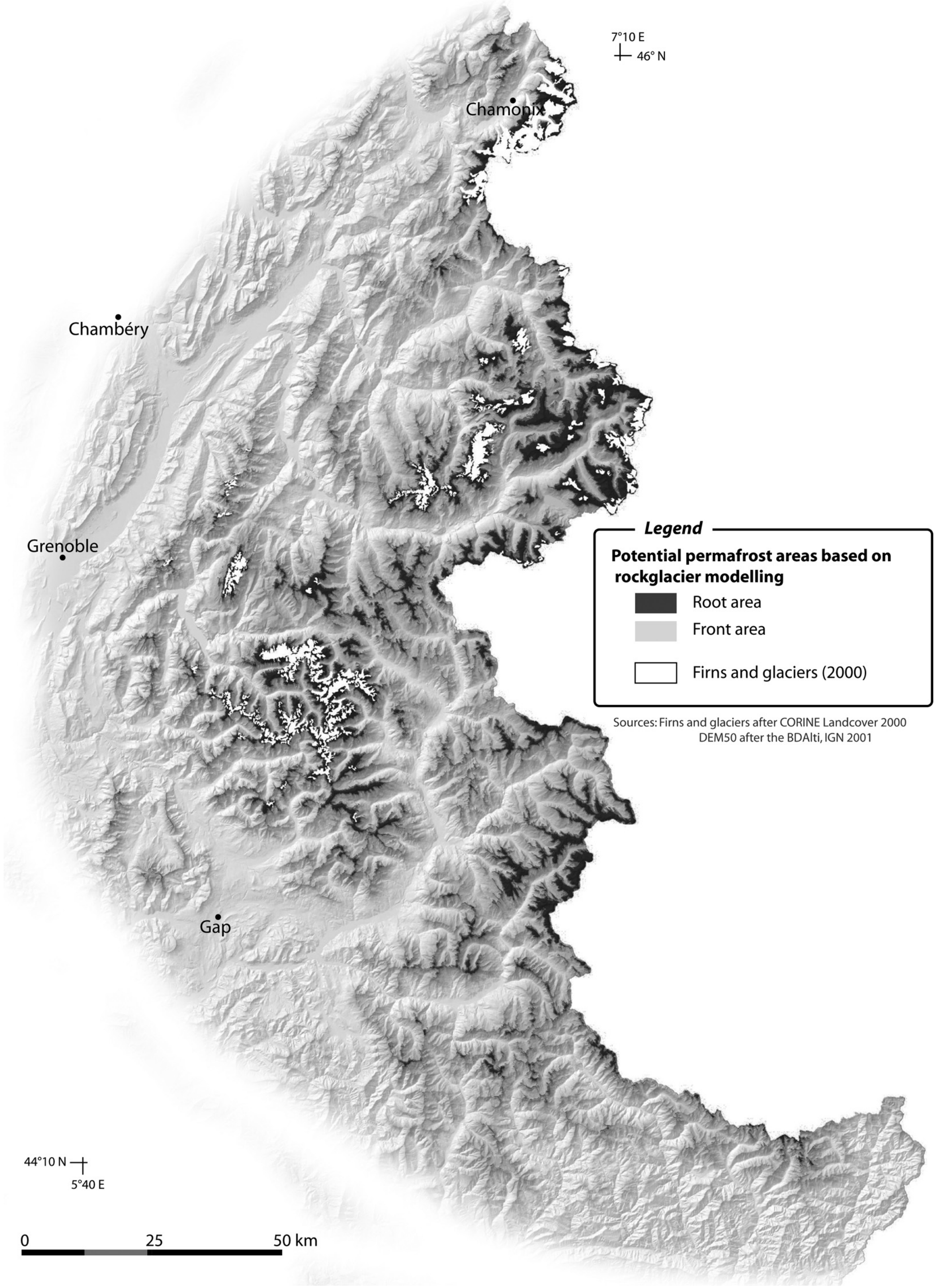

Figure 1. Map of the potential permafrost distribution in the French Alps.

6.3

The Flims Rockslide 3D terrain modelling and volume calculations with GIS-application

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The Flims rockslide is to be known as the largest mass movement in the Alps. Recent studies support the hypothesis of an early Holocene age of this mega-event by radiocarbon dates centred around cal. 9450 BP (Deplazes, Anselmetti & Hajdas 2007). At that Preboreal time climate already has changed to warmer conditions and therefore a readvance of the main valley glacier of Vorderrhein as well as from small local glaciers can be excluded from having reworked the rockslide area (Poschinger et al. 2006). Despite of various new findings up to now the paleogeographic framework, especially the former shape of the pre-existing Flimserstein is poorly established.

Based on geologic evidence (geol. maps, profiles) and geomorphologic considerations (i.e. extrapolation of slopes) in this study a new effort was made to rebuild and reconstruct the former 3D-topography of the Flims area within a GIS (Geographic Information System). This approach allows to determine with enhanced precision the dimensions of this extraordinary rockslide event and to reveal in more details the various processes involved.

The 3D terrain models yielded a total volume ranging from 7 km^3 up to 7.3 km^3 for the breakout zone of the rockslide. The volume of the deposition zone on the other hand gave, according to different scenarios, values between 8.6 km^3 to 9.3 km^3. In addition about 1.5 km^3 of the rockmass was eroded later on by the Vorderrhein river.

During the Flims rockslide the pre-existing valley infill, supposedly saturated completely by water, was squeezed out and mobilised between Sagens and Bonaduz, subsequently being deposited as a special facies type, known as ”Bonaduzer Schotter“ (Abele 1997). Approximately 20 percent of the alluvial valley fill was evacuated directly by the impact of the rockslide. Accordingly, the debris mass does not reach the basement of the Vorderrhein valley but seems to rest on a layer of relict alluvial sediments. The 3D-reconstructions of the Flims topography resulted also in modelling former lakes with their maximum levels, triggered and dammed by the rockslide event. Various 3D-visualizations of the study area certainly will launch fruitful discussions on the dynamics, the processes and the geologic consequences of this famous Flims event.

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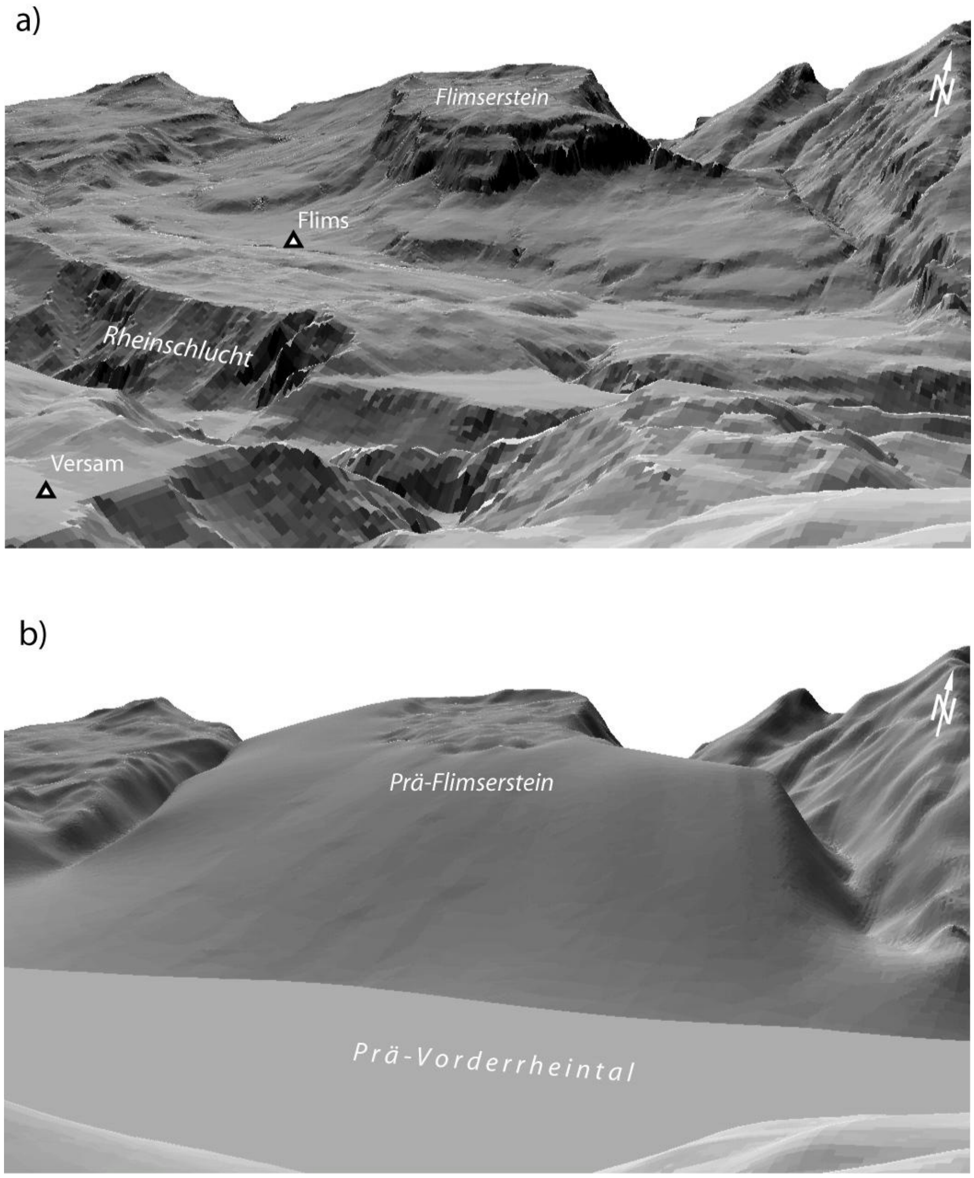

Figure 1: 3D-reconstructed terrain surface of the Pre-Flimserstein. a) Digital terrain model of the Flims rockslide area with the Flimserstein in the background and the partially eroded rock mass in the foreground. b) Reconstruction of the Pre-Flimserstein and the Vorderrhein valley before the rockslide event.

6.4
Erosion-driven uplift of the modern Central Alps

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We present a compilation of four sets of data of modern tectono-geomorphic processes in the Central Alps of Switzerland that appear to suggest that rock uplift is a response to climate-driven denudation in the absence of active convergence. These are (1) basin-averaged Late Holocene denudation rates determined from cosmogenic nuclides and from suspended river loads; these slightly exceed, but spatially mimic the pattern of rock uplift rates as determined by geodetic leveling; (2) the geodetic reference point is also the geomorphic base level with respect to erosion; we further present (3) a compilation of modern plate motion velocities shows that the rotation pole of the Adriatic plate is located within the area, hence the area is not under convergence; finally (4), we illustrate that the Central Alps have acted as a closed system for Holocene sediment redistribution up to the peri-Alpine lakes which have operated as a sink for the erosion products of the inner Alps.

While a variety of hypotheses have been put forward to explain the Central Alpine uplift (e.g. lithospheric forcing by convergence or mantle processes; ice melting) we show with a numerical isostatic model that the correlation between erosion and crustal uplift rates reflects a positive feedback between denudation and the associated isostatic response to unloading. Therefore erosion does not passively respond to advection of crustal material as might be the case in actively converging orogens. Other forces need to be considered to drive surface erosion. We suggest that the geomorphic response of the Alpine topography to glacial erosion and the resulting disequilibrium for modern channelized and associated hillslope processes explains much of the pattern of modern denudation and hence rock uplift. Therefore, in a non-convergent orogen such as the Central European Alps, the observed vertical rock uplift is primarily a consequence of passive unloading due to erosion.

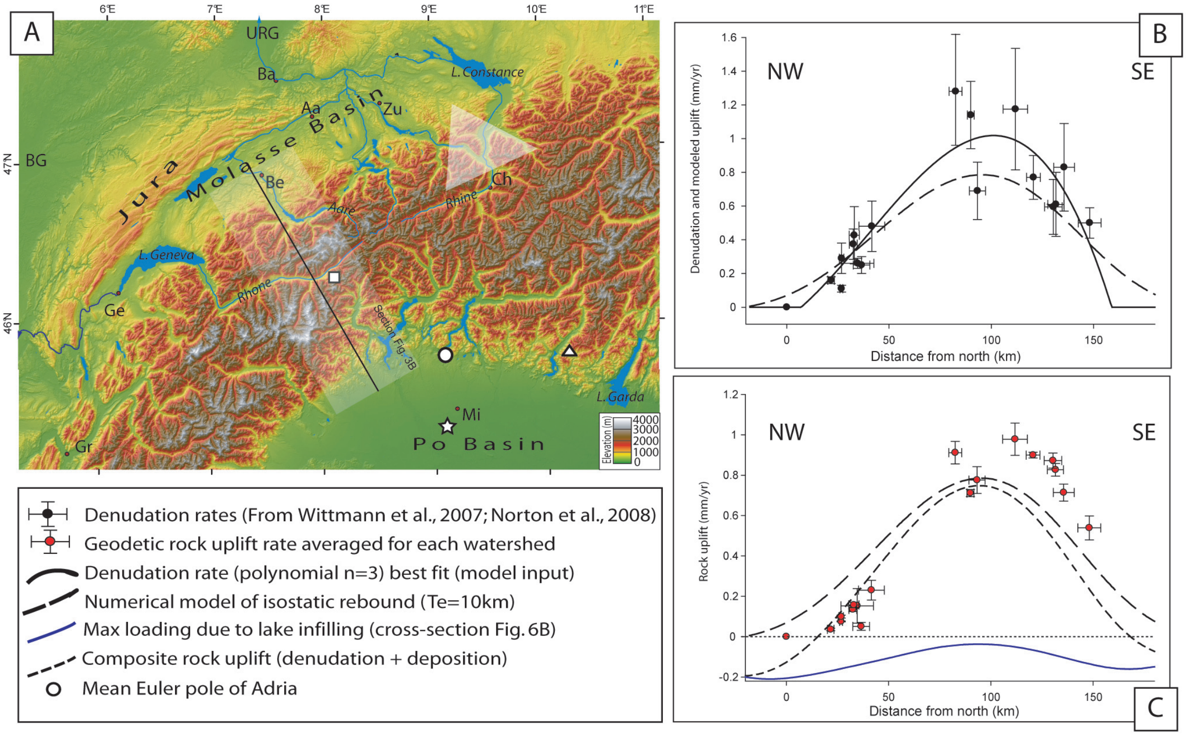

Figure 1. A) DEM of the Central Alps, location of Euler pole of Adriatic microplate (white circle), based on the average of 3 kinematic studies (white triangles, Anderson and Jackson, 1987, square, Battaglia et al., 2004, and star, Calais et al., 2002). Also shown is the section across the belt used in numerical models.
B) Modern denudation rates from cosmogenic radionuclides (Wittmann et al., 2007, Norton et al., 2008) and polynomial best fit to the data. Dashed line is the numerical solution of erosional unloading.
C) Models of isostatic rock uplift induced by modern erosion (long-dashed line) and lake deposition (blue line). The composite solution (short-dashed line, erosion + deposition) is compared with geodetic rock uplift (red dots).

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6.5

First results of firn temperature measurements in 2008 on Colle Gnifetti, Monte Rosa, Switzerland

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At the end of the 19th century and into the beginning of the 20th century, it was assumed that all glaciers in the Alps are temperate, although (Vallot 1893, 1913) observed in the Mont Blanc area that cold firn on high altitude mountain tops is widespread. In the 1950s, Fisher published several articles (1953, 1954, 1955, 1963) about cold firn observations in the Monte Rosa area as did Haefeli & Brentani (1955) for the Jungfrau area. In the 1970s (Lliboutry et al. 1976) and (Haeberli 1976) were the first scientists who systematically investigated the distribution of cold ice and firn in the Alps. In the last 20 years, research activities have started to increase in the cold high-mountain accumulation areas in the Alps, many studies have been undertaken in connection with hazards and core drillings (Alean et al. 1983, Böhlert 2005, Haeberli & Funk 1991, Laternser 1992, Lüthi & Funk 1997, Lüthi & Funk 2000, 2001, Oeschger et al. 1977, Schwerzmann 2006, Suter 1995, Suter et al. 2001a, Suter et al. 2001b, Suter 2002, Suter & Hoelzle 2002, 2004, Suter et al. 2004, Vincent et al. 1997, 2007).
Currently, there are two sites where such measurements have been repeatedly made: Col du Dôme in the Mont Blanc area (Vincent et al. 2007) and Colle Gnifetti in the Monte Rosa area. Colle Gnifetti is a very wind-exposed firn saddle with accumulation rates of 0.3 to 1.2 m water equivalent per year (Lüthi 2000).
On Colle Gnifetti, several boreholes were drilled in vicinity of the saddle point and, until now, measurements were made in 1976, 1982, 1991, 1994, 1995, 1999, 2000, 2003 and 2007. This summer (2008), new field-work has been carried out on Colle Gnifetti. Nine boreholes were drilled with a steam drill and borehole temperatures were measured. These temperatures are now ready to be compared with some older data to detect possible changes.

6.6

Snow temperatures: measurement and modelling

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Both measuring and modelling snow temperatures within the topmost centimetres of the snowpack is a challenge. Snowpack evolution, and in particular snow metamorphism, heavily depend on the temperature distribution near the surface of the snowpack.

Short wave radiation penetrating the snowpack is picked-up by the sensors that heat up. A careful sensor design is thus required and we present two of them: the first allows for highly depth-resolved temperature profiles while the second is suitable for accurate continuous measurements over a few days.

Daily temperature cycles within the top 30 to 50 cm are due to both energy exchanges at the surface and to short wave radiation penetrating the snow. SNOWPACK, the Swiss snow-cover model, treats the latter as a volume source of heat, alike refreezing. We will show how the multi-band parameterization of short wave absorption implemented in SNOWPACK can be optimized by comparing model outputs to reliable measurements of snow temperatures.

6.7

Combined LiDAR and photogrammetry for stability-related change detection in glacierised and frozen rock walls - A case study in the Monte Rosa east face

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Often, rock walls in high-mountain areas are in large parts covered by steep glaciers and firn fields and are under permafrost conditions. Impacts on surface and subsurface ice in such flanks from climatic and other changes strongly influence stress and thermal fields in rock and ice, geotechnical parameters as well as the hydraulic and hydrological regime and may eventually lead to slope instabilities and enhanced mass movement activity such as major ice and rock avalanches (Gruber and Haeberli, 2007; Fischer and Huggel, 2008). The dynamics and changes of steep glaciers and ice cover in high-mountain rock walls and their interactions with the underlying bedrock are very complex and still incompletely understood (Wegmann et al., 1998; Pralong and Funk, 2006; Fischer et al., 2006).

The Monte Rosa east face, Italian Alps, is the highest flank in the European Alps (2200–4600m a.s.l.) and is a prominent example for strong changes and instabilities in a high alpine rock wall. Steep glaciers and firn fields cover large parts of the wall. Since the last glaciations maximum during the Little Ice Age (i.e. since approximately 1850) until the 1980s, the glaciation has changed little. During recent decades, however, the ice cover experienced an accelerated and drastic loss in extent and thickness and some glaciers have completely disappeared within short time (Kääb et al., 2004; Fischer et al., 2006). Over the recent two decades, new instabilities developed in bedrock as well as in ice. The mass movement activity increased drastically since about 1990, culminating in major mass movements in August 2005, with an ice avalanche of more than 1x106 m^3, and in April 2007, with a rock avalanche of about 0.3x106 m^3.

Acquisition of high-quality data is essential to better understand the predominant processes and hazards but is a major challenge in such high-mountain rock walls are very difficult due to topographic conditions, ice cover, and terrain that is difficult and dangerous to access. Therefore, remote-sensing based investigations are fundamental for an integrative assessment of changes in ice cover and bedrock as well as of slope instabilities in such flanks.

The main objective of the presented study is the investigation of changes in bedrock and glaciation in the Monte Rosa east face based on multi-temporal digital terrain models (DTMs) and terrestrial and aerial photographs. For this purpose, high-resolution DTMs of the Monte Rosa east face were photogrammetrically generated from aerial photographs of the years 1956, 1988 and 2001.
In 2007, a helicopter-borne light detection and ranging (LiDAR) scan of the entire Monte Rosa east face could be achieved. Further high-resolution DTM data stems from an airplane –borne LiDAR campaign in 2005. Based on the comparisons of DTMs and photographs over the last 50 years, the spatio-temporal changes in surface topography are evaluated and quantitative assessments of mass wasting and mass accumulation are performed. This unique multi-temporal data set gives an insight in the complex stability, dynamics and mass balance cycles of steep glaciers. Additionally, complex process interactions between different processes in bedrock and ice can be detected from the image data available.

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6.8
Lateglacial glacier evolution of the Greina region (Central Swiss Alps)

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The Greina region is well known because of its importance in the Swiss nature protection history. In spite of the interesting natural features of the region, only few scientific researches were carried out until now, particularly in the field of geomorphology. The aim of this research (Fontana 2008) was to reconstitute the lateglacial glacier evolution of the Greina region, in order to fill a gap in the geomorphological knowledge of the Central Swiss Alps and to make available basis scientific information for the promotion of the Greina geomorphological heritage.

A large-scale geomorphological map of the whole region was first realised; special attention was accorded to the cartography of glacial landforms. On the basis of the cartography of moraines and other glacier-related deposits, a reconstitution of the lateglacial positions of glaciers was realised.

Four main lateglacial glacier positions were identified (Figure 1). One of these positions is characterised by a complex ice origin, whereas the other ones correspond to ancient positions of the Gaglianera glacier and of a disappeared glacier located NE of the Pizzo Coroi. For each glacier position, the Equilibrium Line Altitude (ELA) depression related to the reference phase of 1850 (Maisch, 1992) was calculated. The comparison of the ELA depression of each glacier position allowed us to establish a regional regression sequence including three phases (Table 1). The results were then compared with regional regression sequences established by Maisch (1981) in the Eastern Swiss Alps and by Renner (1982) in the Gothard region (Table1).

Greina	*ELA dep. (m)*	*Eastern Swiss Alps*	*ELA dep. (m)*	*Gothard*	*ELA dep. (m)*
(Fontana, 2008)		*(Maisch, 1981)*		*(Renner, 1982)*	
Greina 1a	110	*Bockten*	100-150	*Alpe di Cruina*	116
Greina 1b	210	*Egesen*	170-240	*Manio*	200-240
Greina 2	310-350	*Daun*	250-350	*All'Acqua*	280-315

Table 1: Comparison of the Greina regional regression sequence with regional regression sequences established by Maisch (1981) and Renner (1982).

The glacier positions and the regional regression sequence allowed the reconstitution of a general lateglacial glacier evolution of the Greina region. An important change in the general ice-flow directions certainly happened between the Last Glacial Maximum (LGM) and the Lateglacial. The general ice-flow coming from the Rhin-source ice-cap recognised by Florineth & Schlüchter (1998) was certainly substituted by a regional ice-flow. The general ice-flow had a NNE-SSW direction in the Plaun la Greina region during the LGM and a SSW-NNE direction during the Lateglacial. During the Greina 2 phase, the Gaglianera, Coroi and Terri glaciers were confluent and formed a front in the middle of the Plaun la Greina region. During this phase, a glacier located NE of Pizzo Coroi occupied the Crap la Crusch depression. Concerning the Greina 1a and Greina 1b phases, only the positions of the Gaglianera glacier could be reconstituted. The front of the glacier was certainly located W of the Plaun la Greina region during both phases.

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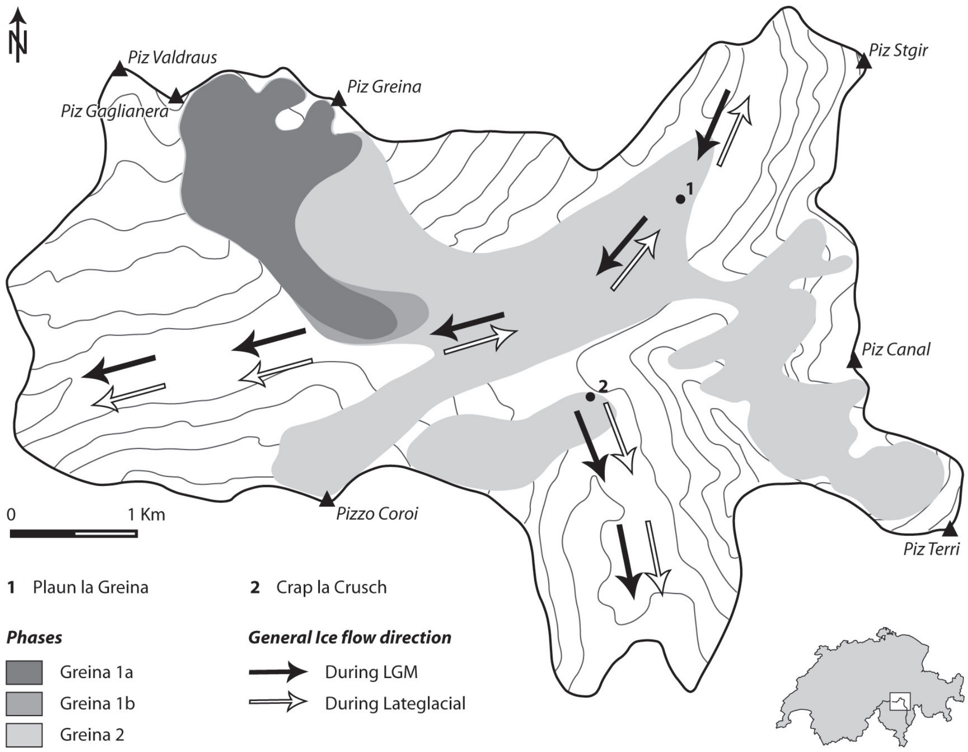

Figure 1. General ice flow direction during LGM and lateglacial phases in the Greina region.

6.9

Geomorphological map of the Greina region (Central Swiss Alps)

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The Greina is a high mountain region located in the Central Swiss Alps. In spite of the interesting geomorphological features of the region, no scientific research was carried out in this field until now. The aim of this research was to realise a geomorphological map of the Greina region, in order to reconstitute the morphogenesis of the area and to make available basis information for the promotion of the geomorphological heritage of the Greina region (Fontana 2008).

The geomorphological map was realised using the guidelines developed at the Institute of Geography of Lausanne University (Schoeneich et al. 1998). The method allows the realisation of morphogenetic maps and is particularly interesting for morphogenesis reconstitutions.

The Greina region presents a rich geomorphological diversity including structural, fluvial, gravitative, karstic, glacial, periglacial and organic landforms. The landform distribution is largely dependent on geological structure. From a tectonic point of view, the northern part of the study area belongs to the Gothard Massiv. This tectonic unit is composed of crystalline rocks, especially gneiss. Crystalline rocks are quite resistant to erosion and still conserve the traces of glacial erosion. Roches moutonnées and striations are therefore very frequent. The tectonic units situated southern of the Gothard Massiv include its sedimentary cover and some lower Penninic nappes. The autochthon sedimentary cover is mostly composed of dolomitic rocks, which present several karstic landforms, like dolines and residual landforms. The parautochton sedimentary cover and the lower Penninic nappes include several lithologies. Calcschists are very frequent: as these rocks are sensitive to the action of frost, erosional glacial landforms are quite rare, whereas talus slopes are very frequent. As clays are a product of calcschists weathering, well-developed solifluxion lobes are also visible.

Thanks to the geomorphological map and to other field observations, the general morphogenesis of the Greina region during the Lateglacial and the Holocene could be reconstituted (for the Lateglacial, see Fontana et al. 2008). During the Holocene, glacial processes became less important, whereas gravitative, fluvial and periglacial processes strongly shape the current evolution of landscape. At the beginning of Holocene, the whole region should have been concerned by a paraglacial morphogenetic crisis. An important glacial sedimentary stock should have been reworked by fluvio-glacial and fluvial processes, while rockfalls and landslides should have been numerous. The fluvial rework of glacial sediments is at the origin of two relict paraglacial alluvial fans outside of the Gaglianera (Figure 1) and Canal valleys. At the same time, the frost and gravity action should have contributed to the talus slope formation. The rivers also shaped progressively their talwegs and the dissolution of dolomite rocks shaped karstic landforms. The current sedimentation level is lower than it was at the beginnings of Holocene and corresponds to the Piano della Greina, Plaun la Greina and Alpe di Motterascio alluvial plains. Concerning glaciers, their Holocene evolution is not well known. Since 1850, they present a strong regression (Maisch 1992) and occupy today a very small part of their glacial cirque (Fontana 2008).

Figure 1. The Gaglianera paraglacial alluvial fan (on the right), and the current alluvial fan (on the left).

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6.10

Observation of the Cryosphere – Switzerland's contri-bution to the Global Climate Observing System GCOS

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In recent decades – especially following the adoption of the UN Framework Convention of Climate Change (UNFCCC) in 1992 – the demand for observations of climate change and the closer links between climate observation and climate research/modeling has steadily increased, leading to the establishment of the Global Climate Observing System (GCOS).

GCOS is an initiative of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the UNESCO, the UN Environmental Programme (UNEP) and the International Council of Science (ICSU). GCOS is designed to ensure that the observations and information needed to address climate-related issues are obtained systematically and made available to all potential users. In particular, GCOS follows the aims and requirements of systematic observation as specified in the UNFCCC and the Kyoto Protocol.

In Switzerland, the Swiss GCOS Office at the Federal Office of Meteorology and Climatology MeteoSwiss was established in 2006, following the ratification of the Kyoto Protocol in 2003, to coordinate climate observations at the national level and to foster information exchange and collaboration among the various institutions. In 2007, the Swiss GCOS Office has compiled the first-ever inventory of the country's long-term climatological data series of the atmosphere and the land surface, entitled "National Climate Observing System (GCOS Switzerland)" (Seiz & Foppa, 2007). Switzerland has a long tradition in the observation of cryospheric parameters, including more than 100 years of glacier and snow depth measurements, the longest Central European lake ice cover records, the permafrost monitoring network PERMOS, the world's longest snow water equivalent series for catchment areas, and is additionally hosting the important World Glacier Monitoring Service.

Our presentation will give an overview about GCOS in general and about the Swiss GCOS activities. It will highlight how local measurements of different cryospheric parameters in Switzerland contribute to the Global Climate Observing System and the added-value of satellite-based observations of the cryosphere within GCOS.

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6.11

Replica method for three-dimensional X-ray microtomographic imaging of snow

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Snow microstructure is a crucial factor determining many properties such as mechanical strength, thermal conductivity, or optical properties. There are basically three techniques used to measure the full three-dimensional microstructure of snow samples: serial sectioning, direct X-ray computer tomography (micro-CT), or micro-CT of 1-chloronaphthalene cast snow. Samples that need to be transported or stored must be conserved by casting the snow with a solidifying substance, e.g. 1-chloronaphthalene or diethyl phthalate (DEP). Chloronaphthalene, while having a good X-ray contrast, is quite toxic and smells bad.

Image processing of serial sections of DEP cast snow is often very difficult, due to the formation of DEP crystals that appear optically very similar to ice crystals. Micro-CT was so far not applicable to DEP cast snow samples because there is hardly any absorption contrast between ice and DEP.

We developed a new replica method that allows investigating the microstructure of DEP cast samples by micro-CT. The sampling and casting process can be done as usual. Before the micro-CT measurement, the ice needs to be removed from the cast samples. The vapour pressure of DEP is about a million times smaller than that of ice, which allows sublimating the ice selectively. Keeping the sample under vacuum accelerates the sublimation process drastically to a few days. This leaves behind the DEP, which forms an exact negative image of the snow. The porous structure can now be measured in the micro-CT. A numerical inversion of the segmented micro-CT images yields a digital replica of the original snow structure.

The accuracy of replication was tested by comparing the digital replica to the original snow structure. The structural parameters of the two structures were compared to each other. The replication of the snow microstructure was very good with relative errors below 5%. The presented replica method is comparably straightforward and, for the snow types tested, the microstructure is accurately reproduced.

6.12

The ice ridge at Murtèl/Corvatsch: Studying a (c)old archive

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Cold cornice-, crest- and plateau-type miniature ice caps of the northern hemisphere are known to contain old (Holocene to even Pleistocene) ice layers. These small but highly interesting paleoglaciological and paleoclimatical archives, however, are still largely unexplored and their future response to the rapid warming of the atmosphere remains to be investigated. On the north-south-oriented ice ridge Murtèl/Corvatsch (3300 – 3500 m.a.s.l) in the Upper Engadin, systematic studies are performed since several years (Haeberli et al. 2004). In this contribution we like to sum up the investigations and findings, present new results and discuss potential future research questions.

Refreezing of melt water is the main accumulation process, resulting in small accumulation rates. Temperatures in boreholes and at the marginal ice/rock-contact reveal that the ridge consists of cold ice and is frozen to the permafrost-bedrock (no basal sliding). Finite elements modelling shows that only very small flow velocities can be expected under the ridge where the surface slope tends towards zero. These two findings (small accumulation rates and probable ice velocities close to zero at the ice/rock interface) indicate that basal ice layers may have a considerable age (millennia). These assumptions are supported by a C14 date from an ice core drilled down to the bedrock in 2007, which however, since being a preliminary result, needs to be confirmed by further analyses.

A GPS survey was performed in 2000 and repeated in 2007. Comparison of the two digital elevation models (DEM) showed an average subsidence of the surface of about 5m (≈0.7m/y) with a maximum lowering of > 15 m and a geometric distortion of the ridge. Analyses of the Tritium content show that the ice at the surface in 2007 dates back to around 1960, which means that the ice accumulated in the last four to five decades has already melted away. Ground penetrating radar (GPR) measurements from 2001 indicate ice thicknesses of about 30m (±20m) under the ridge and more shallow parts at the glacier margins. Continuation or even acceleration of recent thinning rates would, hence, lead to vanishing of the glacier within decades.

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6.13

Application of operational geophysical monitoring systems on alpine permafrost

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Determining the subsurface ice and unfrozen water content in cold regions are important tasks in all kind of cryospheric studies, but especially on perennial (permafrost) or seasonal frozen ground, where little insights can be gained from direct observations at the surface. In the absence of boreholes, geophysical methods are often the only possibility for "visualising" the subsurface characteristics, and their successful application in recent years lead to more and more sophisticated approaches including 2- and 3-dimensional monitoring and even quantifying the ice and unfrozen water content evolution within the subsurface (for an overview see Hauck & Kneisel 2008).

Due to the strong sensitivity of electrical resistivity and permittivity to the phase change from unfrozen water to ice, the application of electrical and electromagnetic techniques has been especially successful. Within these methods, Electrical Resistivity Tomography (ERT) is often favoured due to its comparatively easy and fast data processing, its robustness against ambient noise and its good performance even in harsh, cold and irregular environments. Numerous recent studies have now shown that ERT is principally suitable to spatially delineate ground ice, differentiate between ice-poor and ice-rich occurrences, monitor freezing, thawing and infiltration processes, and even determine the origin of the ice, i.e. a differentiation between buried glacier ice and segregation ice, due to their different ion contents (yielding a reduced electrical resistivity for the latter).

In the context of a possible increased frequency of extreme weather periods, such as the hot summer 2003 in the European Alps, a monitoring of cryospheric components such as the mountain permafrost evolution becomes more and more important (Hilbich et al. 2008a). Common observation techniques are usually based on the thermal aspects, as in existing permafrost borehole temperature monitoring networks. Concerning the impacts of changing climate parameters, not only temperature but especially the ice and water content of the subsurface plays an important role, especially for permafrost observation purposes.

In summer 2006 the installation of a semi-automatic ERT monitoring system has been completed at 4 permafrost sites in the Swiss Alps (in co-operation with the Swiss permafrost network PERMOS, Vonder Mühll et al. 2007). This geophysical monitoring network serves to investigate the sensitivity of characteristic morphological sites to extreme atmospheric forcing in order to estimate the long-term evolution due to climate induced warming. Monitoring profiles are located at a rockglacier (Murtél, Upper Engadine), steep slope (Schilthorn, Bernese Alps), talus slope (Lapires, Valais) and frozen bedrock (Stockhorn plateau, Valais)(Hilbich et al. 2008b). The geophysical monitoring strategy includes repeated ERT measurements with a monthly to seasonal resolution over several years, as well as annual refraction seismic measurements at all sites. Whereas relative resistivity changes with time can be attributed to freeze and thaw processes, combined ERT and refraction seismic tomography will serve to determine total fractions of ice, unfrozen water and air within the pore space of the respective subsurface sections (Hauck et al. 2008).

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6.14

Thermal conductivity of snow: How to find a better parameterisation?

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The thermal conductivity of snow is an important parameter in the energy balance of snow-covered areas. This energy balance is a key to understanding the response of arctic regions to changing global climate. The thermal conductivity and the heat flow through snow also determine the temperature gradient metamorphism which modifies the microstructure of snow (Schneebeli & Sokratov 2004; Kaempfer et al. 2005). As a consequence, mechanical, thermophysical, chemical, and optical properties of the snow are changed. For modelling the metamorphism of snow, it is essential to use a realistic parameterisation for the thermal conductivity. An understanding of the relationship between heat flow and snow microstructure is crucial for improving models in climatology, interpretations of chemical signals in firn and ice, and for avalanche research.

Available data for the effective thermal conductivity of snow, k_{eff}, are mostly based on measurements with a transient method using a needle probe (e.g. Sturm et al. 1997). They relate keff empirically to the density. However, the measured values differ by up to a factor of five for snow with the same density and the same grain shape. Thus, a large uncertainty is introduced into models that use a parameterisation based on these measurements. Furthermore, new measurements using a steady state method with heat flux plates suggest values of k_{eff}, that are significantly higher than those measured by Sturm et al. (1997). For snow samples with a density of 200-300 kgm^{-3}, a k_{eff}, of 0.2-0.3 $Wm^{-1}K^{-1}$ was measured.

In our study, we systematically compare measurements of k_{eff}, with a needle probe (transient method) and with heat flux plates (steady state method) for different snow types and snow densities. The microstructure of the snow samples is characterized with micro computer tomography (micro-CT). Based on the assumption that the bonds between grains are more important than the density of the snow, Dadic et al. (2008) suggest a correlation between the penetration resistance and the thermal conductivity of snow. We test this correlation by measuring the penetration resistance of the different snow types using the SnowMicroPen (SMP), a high resolution penetrometer (Schneebeli & Johnson 1998), and correlating these measurements to the measured thermal conductivity.

Contact problems between the probe and the snow sample may be a potential explanation for the observed differences between the measurement methods. This effect is expected to be especially pronounced in fragile snow types such as depth hoar. The contact geometry between the probe and the snow sample is investigated using micro-CT.

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6.15

Thermal and electrical properties of a periglacial talus slope

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Les Attelas talus slope is located on the western flank of the Mont Gelé (3023 m a.s.l.), in Verbier area. This cone-shaped landform is affected by solifluction in the upper-mid part of the slope, whereas bulging suggests the presence of creeping permafrost in the lower part of the slope.

In order to determine the spatial extension and the characteristics of the permafrost within the slope, several thermal and geoelectrical measurements have been carried out (Lambiel 2006).

Ground surface temperatures measured in March 2005 at the base of the snow cover (BTS method) displayed values colder than -6°C below 2700 m a.s.l. (Fig. 1). In the upper portion of the slope, temperatures were warmer (up to -1°C). According to these values, permafrost may be present in the lower part of the slope, whereas the probability of its presence decreases upslope.

In summer 2007, 48 permanent electrodes were installed each 4 meters along an upslope-downslope profile in order to monitor the underground resistivity using the Electrical Resistivity Tomography (ERT) technique (Fig. 1). The ERT profile (Fig. 2) shows that the highest resistivities are located in the lower part of the slope. From the distance of 85 meters to the foot of the slope, a resistive body with values higher than 25 kΩm and thickness of about 15 meters has been imaged by both apparent resistivity and inversed resistivity. It corresponds to the cold BTS temperatures (Fig. 1) and can be interpreted as a permafrost lens. In the middle of the ERT profile, the lower resistivities (<10 kΩm) measured below 15-20 m depth are interpreted as unfrozen sediments. In the upper section, the resistive body is still present, but is found at greater depth and the resistivity values are lower (12-20 kΩm). This may be interpreted either as low-resistivity permafrost or as porous sediments. In the uppermost part of the profile, the resistivities lower than 4 kΩm indicate the absence of frozen sediments.

The permafrost distribution pattern evidenced in Les Attelas talus slope is conform to the measurements carried out in other alpine talus slopes (e.g. Otto and Sass 2006, Lambiel and Pieracci 2008). Permafrost appears likely in the lower part of the slopes, whereas it is generally absent upslope. In order to get direct information on the ground characteristics and thermal regime, 3 boreholes will be drilled along the ERT profile.

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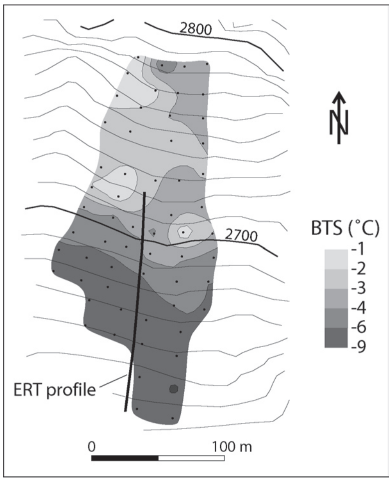

Figure 1. BTS measurements in March 2005 (black dots) and location of the Electrical Resistivity Tomography profile (black line) in Les Attelas talus slope.

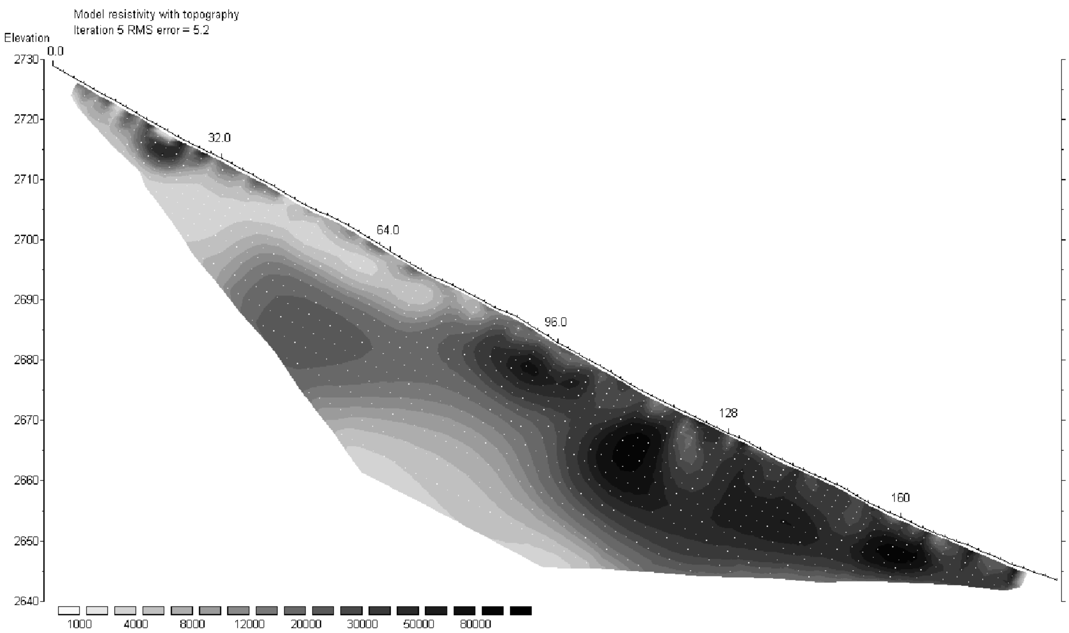

Figure 2. Electrical resistivity tomogram in Les Attelas talus slope, July 2008. The colour scale represents inverted resistivities in Ωm.

6.16

Modelling of glacier bed topography from glacier outlines and DEM data in a GIS

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Due to the ongoing and expected future increase in global mean temperature, the Alpine environment will continue to get further away from equilibrium. This could have large environmental and societal impacts. Glaciers are a part of the high-mountain cryosphere, and their changes are considered to be the best natural indicators of climatic changes. The observation of the high-mountain environment and its glaciers forms thus an important part in global climate related observing programs. The calculation and visualization of future glacier development is thus an important task of communicating climate change effects to a wider public (Paul et al., 2007).

One of the most challenging topics in the assessment of climate change impacts on future glacier development is the unknown glacier bed and the related uncertainties in glacier volume estimations (Driedger and Kennard, 1986). In this respect, an estimated topography of the glacier bed would facilitate the calculation of glacier volume, the detection of local depressions, and the visualization of future ice-free grounds. While several methods exist to obtain a glacier bed from modelling combined with measurements (e.g. Huss et al., 2008), the goal of this study is the application of a simple but robust method which automatically approximates a glacier bed for a large sample of glaciers, using only few input data such as a digital elevation model (DEM), glacier outlines, and a set of flow lines for each glacier (Fig. 1). It is based on the calculation of the ice thickness along selected points of the flow line from the shallow ice approximation (SIA) following Haeberli and Hoelzle (1995) and subsequent spatial interpolation using a routine (topogrid) that is implemented in a geographic information system (GIS) and was developed by Hutchinson (1989).

Sensitivity tests with simple geometric forms on flat and inclined surfaces helped to constrain the model parameters. This includes the specifications for topogrid as well as the rules for digitizing the flow lines. For Switzerland, they form the only part of the input data that have to be newly created. The model was tested with real data from the Bernina region which lead to some modifications of the flow line digitizing and interpolation process. Finally, the reconstructed beds are compared to glacier beds or thickness measurements for three glaciers (Morteratsch, Gorner and Zinal) which have been obtained in previous studies.

The comparison revealed that the method has a large potential, but further improvements could be integrated as well. The general depth distribution of the reconstructed glacier beds is in a fairly good agreement with the results from the other studies and calculated glacier volumes or the location of local depressions do agree as well. However, there is a tendency to underestimate glacier thickness and locally some strong deviations exist. Currently, mean slope is the only (and thus a very sensitive) variable for the ice thickness calculation. Hence, it might be possible to improve the performance of the method by integrating some basic laws of glacier flow and further geomorphometry-dependent smoothing of the glacier surface (e. g. Huss et al., 2008). However, the method as a whole should stay as simple as possible to facilitate its automated and large scale application.

The application of the (improved and locally calibrated) method to all glaciers in the Swiss Alps does only require that glacier flow lines are digitized according to the rules outlined in this study. In combination with further GIS-based models (e.g. Paul et al., 2007) the here presented method would allow to calculate and visualize impacts of climate change on glaciers and their role as a water resource for Switzerland.

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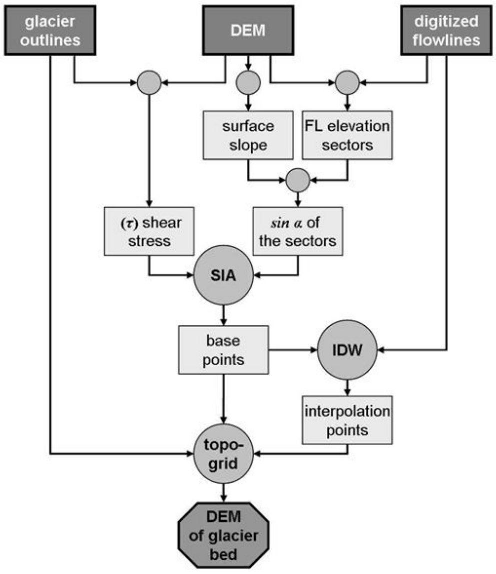

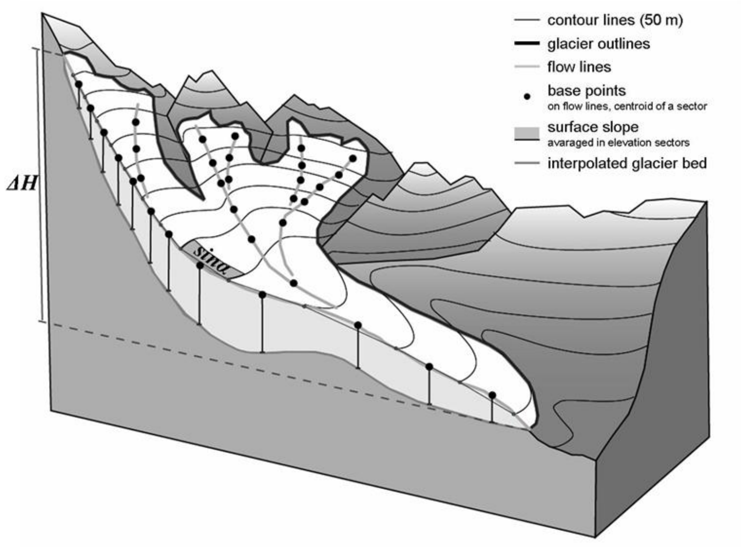

Figure 1: Schematic flowchart and details of the glacier bed modelling.

6.17

Transient response of idealized glaciers to climate variations

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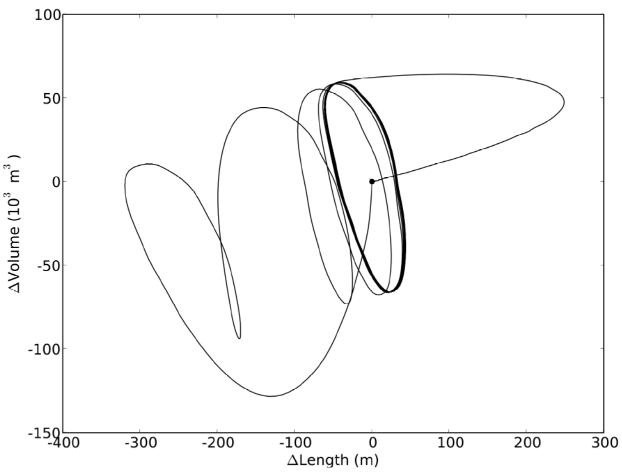
Variations of glacier length and volume under climate variations are investigated with model glaciers on a simple bedrock geometry. Under periodic climate oscillations the well-known phase lags of length and volume are obtained, after initial transients have died out. The relation between glacier mass balance (local or total) and climate is strongly influenced by the transient response for forcing periods shorter than the volume time scale. These transients are surprisingly large, and lead to unexpected trajectories in phase space. Under periodic oscillations the local ice thickness follows the climate forcing with a typical phase delay of 60° (accumulation area) to 180° (glacier terminus), while glacier length is completely out of phase for forcing periods below the volume time scale. The evolution of the model glacier can be approximately described with a forced, linearly damped harmonic oscillator which is typically underdamped. Approximate expressions for the volume- and area time scales are explicitly derived, as are volume-length scaling relations.



Phase space diagram of volume change vs. length change of a model glacier under climate forcing with 50 year period. Only after 5 climate cycles the glacier response approaches the limiting cycle around the steady state (black dot). Obviously climate and glacier reaction are not closely related.

6.18
Airflow velocity measurements in ventilated porous debris accumulations

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The mechanism of deep air circulation (the "chimney effect") is known to be a frequent phenomenon maintaining very cold ground conditions, and sometimes permafrost, in porous debris accumulations (talus slope, relict rock glacier) located several hundred meters below the regional permafrost limit. Temperature measurements at the ground surface (Morard et al. 2008) and in borehole (Delaloye & Lambiel 2007) revealed that the ground thermal regime is strongly influenced by the advective-heat effect of the airflow.
In order to better understand the processes by which internal ventilation causes a strong overcooling of the lower part of debris accumulations, experimental continuous airflow velocity measurements (using anemometers and an air differential pressure sensor) have been carried out recently in three sites : in the Creux-du-Van talus slope (Jura mountains, 1250 m a.s.l.), in the Dreveneuse-d'en Bas talus slope (Valais Prealps, 1560 m a.s.l.) (Delaloye & Lambiel 2007) and in the Gros Chadoua relict rock glacier – talus slope complex (Fribourg Prealps, 1570 m a.s.l.).

Windmill and sonic anemometers were placed in wind holes located in the lower part of the ventilation system. In the Dreveneuse-d'en Bas talus slope, the windmill sensor recorded a velocity of 0.1 – 0.4 m/s in summertime, but stronger aspiration (up to 0.8 m/s) by very cold weather during a snow free period in late fall. In the Creux-du-Van talus slope, data from the sonic anemometer were very noisy, but seem also range between 0.05 - 0.5 m/s and sometimes 1 m/s.
In the Gros Chadoua, both wind sensors recorded outflow values between 0.5 to 1.7 m/s in summer, with faster velocities when the external temperature rises. In fall, before the onset of a snow cover, when the external air temperature crossed a threshold of about +4°C, airflow direction changes rapidly. Airflow reversibility occurred several times during this period, depending on the outside air evolution (figure 1). The wind sensors did not work properly during winter.
The relation between airflow velocity (U) and the outside air temperature is not linear, but can be expressed as : $U = c \sqrt{(\text{Outside Air Temperature} - \text{Reversibility Threshold Temperature})}$ (Ohata et al. 1994). C is an empirical coefficient depending upon structural conditions. For the Gros Chadoua, the results fit well with a coefficient c between 0.25 and 0.5. For Dreveneuse-d'en Bas, results are better with a smaller coefficient (0.10).

When the wind hole was disconnected from the open air environment by a snowcover, the differential pressure sensors revealed for most of all the winter season that the pressure contrast between the inside and the outside was dependant on the external temperature. This pressure low at the base of the snow cover is assumed to be caused dynamically by the ascent of relatively warmer light air throughout the debris accumulation. This process forces the external air to penetrate in the ground through the snow cover in the lowermost part of the system.

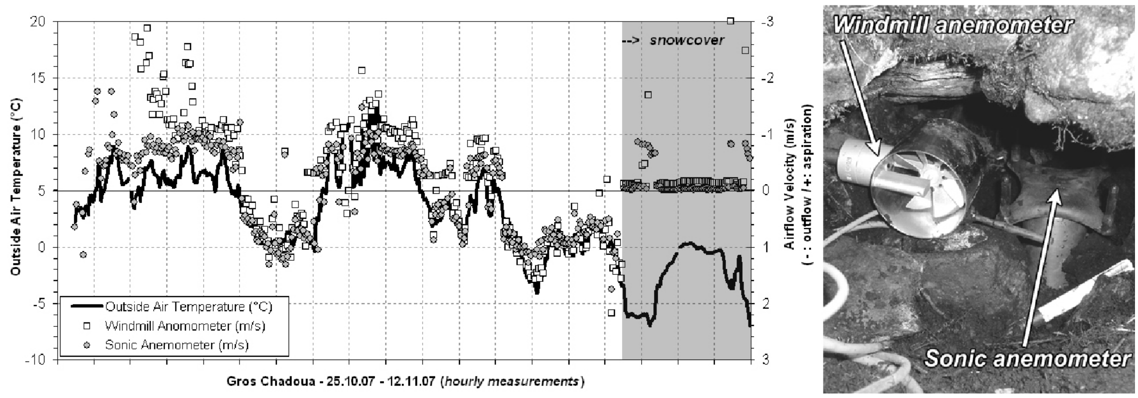

Figure 1. Air flow velocity and direction (outflow or aspiration) linked with the outside air temperature in the Gros Chadoua, between 25. October and 12. November 2007.

Despite these instruments were normally intended for open-air measurements, a range of airflow velocity has been determined. The results show that the airflow is maintained by a simple relation determined by the pressure gradient resulting from temperature difference between the inside and the outside air. The circulation of air inside porous debris accumulation is also a continuous process, even after the development of a snowcover.

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6.19

Inventory of geomorphosites of Bavona and Rovana valleys (Ticino)

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During the last decade, research on geomorphological heritage has improved due to the development of geotourism and geoparks and to the activity of the Working group on Geomorphosites of the International Association of Geomorphologists. Several methods (see Reynard and Coratza, 2007) were developed for assessing the quality of geomorphosites – that is landforms to which a value can be given due to human perception and/or utilization (Panizza, 2001). The aim is to reduce subjectivity and to facilitate the selection of the most representative sites, worth to be protected and/or promoted.
Inspired by several approaches developed during the last decade, Reynard et al. (2007) developed at the Institute of Geography of Lausanne University an assessment method of geomorphosites. The method allows assessing the scientific, ecological, aesthetic, cultural and economic values of geomorphosites and to note more descriptive data in order to set up a site inventory. The assessment is divided in two categories of criteria: the central (scientific value) and additional (ecological, economic, aesthetic and cultural) values.
The assessment method was applied on two alpine valleys in the Southern Swiss Alps. More precisely, we focused on the selection and the assessment of Bavona and Rovana valleys' geomorphosites (Maggia Valley, Ticino). 28 landforms with a scientific central value were identified and studied. Results show that Calnegia hanging valley obtains the most important score and is just followed by the Basòdino Glacier, a small ice cap glacier. One site, the fossil proglacial margin of the Basòdino Glacier W, represents an incredible geodiversity due to the glacio-karstic origin of Pian del Ghiacciaios polje.
After the inventory stage, we noted that, on the ground, geomorphology is not much known in comparison with the high value of some geomorphosites. Thus, in order to acknowledge them by the general public, we offered some perspectives with the intention of promoting the geomorphological heritage of the region. Firstly, the definition of categories of protection would contribute to preserve the vulnerable geomorphosites towards human impacts. Secondly, we underline the value of some interesting sites of the inventory with the idea of promoting a sustainable tourist development. Geodiversity is indeed poorly taken into account for the (geo)tourist development of the region.

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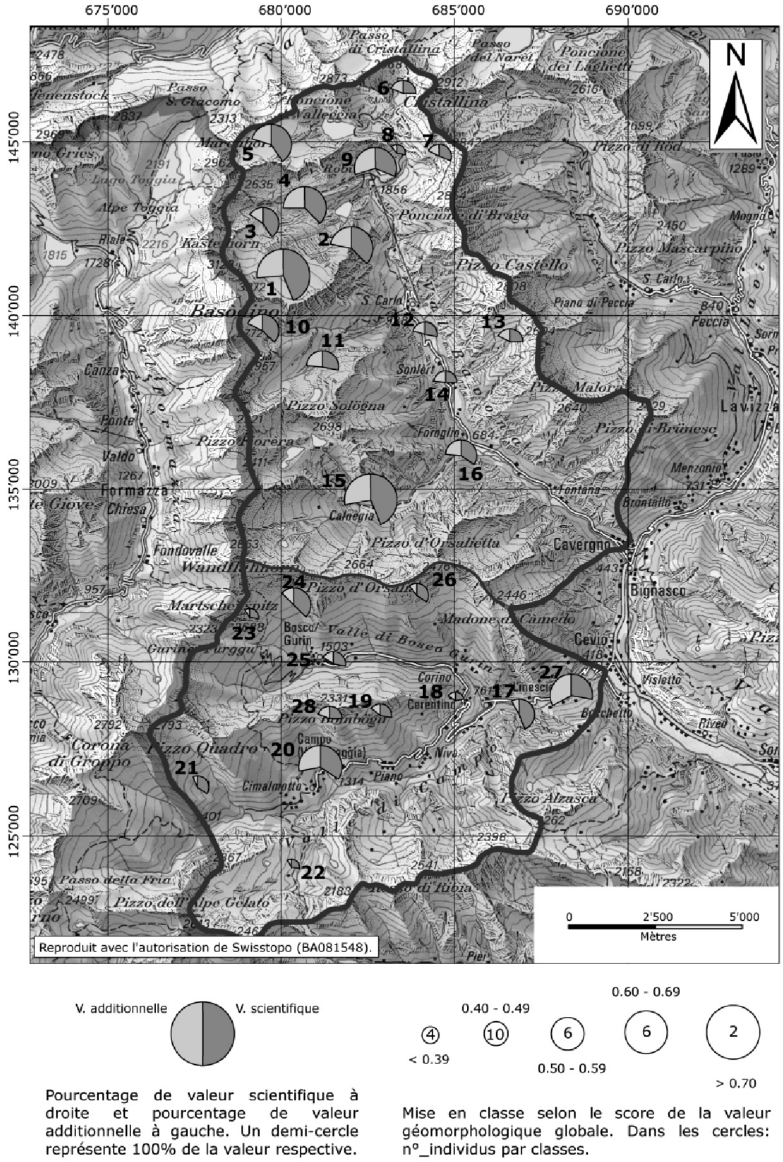

6.20

Evaluation des effets de l'enneigement artificiel sur la chimie du sol: Cas de Crans-Montana-Aminona, Valais

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Ce travail traite des éventuels impacts sur la chimie du sol dû à l'utilisation de l'enneigement artificiel, ainsi qu'à celle d'additif qui permet une production de neige de culture à des températures plus hautes. Le but est de déterminer s'il existe des impacts sur la chimie du sol, par comparaison des résultats d'analyse entre différents profils de sols, soumis et non soumis à l'enneigement artificiel, et d'évaluer l'ampleur de ces derniers s'il existe. La neige artificielle est produite par pulvérisation d'eau mélangée à de l'air comprimée, ce qui forme des microgouttelettes qui vont s'agglomérer sur des noyaux de congélations pour former des cristaux de neige (Brillaud et al., 2005 et Campion, 2002). Il ne semble donc pas qu'un apport en élément, de surcroît polluant, soit à craindre, pour autant que l'eau utilisée ne soit pas polluée (ou que n'y retrouve pas un ou plusieurs éléments dans des concentrations anormalement élevées). Cependant, l'utilisation d'un additif est parfois présente, ce qui était le cas pour une partie des installations du domaine skiable de Cran-Montana-Aminona jusqu'en 2007. L'additif le plus souvent utilisé est une protéine bactérienne appelée INP (Ice Nucleation Protein, Graether et Jia, 2001) produite par Snowmax®. Cette protéine joue le rôle de noyau de congélation, et favorise ainsi la formation de cristaux de neige à des températures plus élevées (soit environ − 2°C au lieu de -4°C sans). Une utilisation croissante de l'enneigement artificielle, lié à l'utilisation, dans certains cas, d'un additif d'origine bactérienne, est bien souvent à l'origine de craintes vis-à-vis de l'environnement. Ce travail ne prétend pas répondre à la question « L'utilisation de l'enneigement artificielle, avec ou sans additif, est-il à l'origine d'une pollution des sols ? », mais, se place plutôt comme un point de départ, afin de déterminer si des impacts directs ou indirects sur la chimie du sols sont imputable à l'utilisation de cette technologie, notamment un apport en composés azotés qui serait lié à la présence de l'additif d'origine protéinique. Nous avons échantillonné trois « types» de sols : soumis à l'enneigement uniquement naturel, à l'enneigement artificiel sans additif et naturel et à l'enneigement artificiel avec additif et naturel, ainsi que différents «types» de neige afin de vérifier l'origine l'apport en certains éléments: neige naturel, neige artificielle sans additif et avec, neige mixte naturelle-artificielle sans additif et avec. Nous avons également échantillonné différentes eaux provenant de ruisseaux alimentés par la fonte de neige naturelle, artificielle avec et sans additif afin d'éventuellement constaté un transfert dans ces eaux (Fig. 1). Dans le but de passer en revue un maximum d'éléments (chimiques) ainsi que les propriétés de base (pH, granulométrie), présents dans le sol, nous avons effectué les analyses suivantes :

- composition en éléments majeurs et traces par fluorescence X
- composition ionique par chromatographie sur extractions
- dosage du carbone total, organique et minéral par coulométrie (sur échantillons solides) et analyseur élémentaire de C dissout (sur extractions)
- analyses CHN (sur échantillons solides)
- analyses qualitatives spécifiquement des composés protéiniques par spectroscopie par fluorescence UV-Visible et absorbance
- dosage de protéines totales par la méthode de Bradford (sur les extractions).

Les résultats montrent que globalement, il existe peu de variations de concentrations des éléments analysés pouvant être corrélés avec l'utilisation de l'enneigement artificiel que ce soit avec ou sans additif. Il n'y a notamment pas d'apports flagrants en composés azotés malgré l'utilisation d'un additif de nature protéinique et d'origine bactérienne. Les seuls éléments dont on peut redouter un apport, du fait que des concentrations relativement élevées dans les échantillons de neige artificielle avec et sans additif, sont le magnésium, le calcium ainsi que le sulfate. Cependant, ce dernier étant un anion, une retention dans les sols est peu probable. Ce dernier se retrouve en concentrations plus élevées dans les eaux de ruisseaux, alimentés par les eaux de fonte de neige mixte, donc avec présence de neige artificielle avec et sans additif. Il est toutefois difficile de corréler ces concentrations plus élevées avec un apport direct dû à l'utilisation de l'enneigement artificiel, aux vues de la dynamique des systèmes d'alimentation des ruisseaux, et de la date de prélèvement des échantillons. Nous pouvons donc conclure qu'un impact sur la chimie du sol (pour la part de ce domaine exploré dans ce travail), n'est pas clairement observable, et est dans tous les cas pas d'une ampleur importante. Cependant, nos résultats nous montrent également qu'il serait intéressant de faire des recherches se dirigeant dans le domaine de la biochimie du sol, plus particulièrement le développement et l'activité bactérienne.

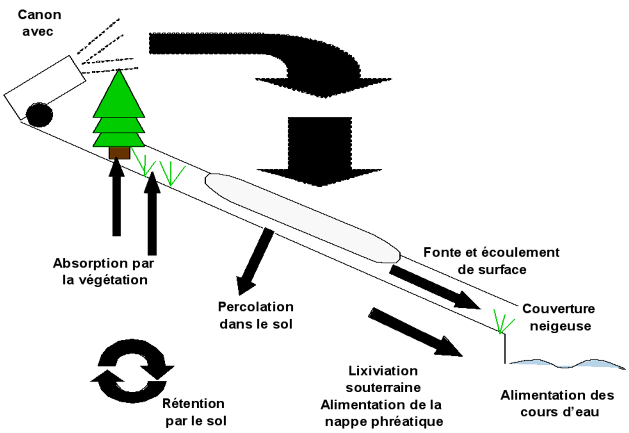

Figure : 1 : Schéma des différentes voies possibles de transfert des composés chimiques de la neige artificielle dans les différents compartiments

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6.21

Spatial variability of glacier elevation changes in the Swiss Alps obtained from differencing two DEMs

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During the past 25 years massive glacier thinning has been observed in the Alps. This is documented by direct mass balance measurements on nine regularly observed glaciers as well as field evidence (e.g. disintegration of glacier tongues, increased areas of rock outcrops, collapsing rock walls, revised hiking trails) at several sites (Paul et al., 2007). However, it remained uncertain how representative the nine directly measured glaciers are for the volume change of the entire Alps. A possible way of assessing the representativity is to subtract two digital elevation models (DEMs) from two points in time which are of sufficient accuracy with respect to the expected changes.

For the Swiss Alps, a DEM with 25 m spatial resolution (DEM25) was generated by swisstopo around 1985. In February 2000 a near-global DEM was acquired by interferometric techniques during the Shuttle Radar Topography Mission (SRTM). This DEM is available for free from an ftp-server at 90 m (or 3") spatial resolution. It offers now the unique opportunity to assess glacier elevation changes over the entire Alps by subtracting it from an earlier DEM (like the DEM25 in Switzerland). It has to be noted that both DEMs could have larger errors in the (snow-covered) accumulation area of glaciers. For the DEM25, the stereo matching of optical aerial photography suffers from poor contrast over snow and the SRTM DEM has some uncertainty due to a variable snow penetration depth of the C-band radar beam.

For mainly two reasons we have not corrected the elevation dependent bias of the SRTM elevations which was reported in earlier studies. One reason is that a similar bias results as an artefact when DEMs of different cell size are subtracted (Paul, in press), the other is that a huge portion of glaciers would get positive elevation changes (mass gains) in the accumulation area, which is highly unlikely during the period 1985 to 1999.

For this study we have calculated glacier specific elevation changes from 1985 to 1999 for about 1050 glaciers larger than 0.1 km^2 in the Swiss Alps (Paul and Haeberli, 2008). The changes refer to the glacier geometry of 1973 which is close to the 1985 glacier extent (Paul et al., 2004) and digitally available for all glaciers in Switzerland. In order to compare the results with the direct measurements, two mean volume change values (in meter water equivalent, m w.e.) are calculated. One is (method A) the arithmetic mean of the individual mean changes of all glaciers and another one is (method B) the mean value for the entire glacierized area that does not consider individual glaciers (all glaciers together are taken as one glacier entity).

The analysis reveals strong thickness losses (partly >80 m) for flat / low-lying glacier tongues and a strong overall surface lowering also for glacier tongues under a thick debris cover. The difference image (Fig. 1) displays fine spatial details of the change.

Apart from the obvious massive downwasting of the tongue of Triftglacier, it clearly reveals that some glaciers (e.g. Stein, Kehlen, Damma) have been larger in 1985 than in 1973 as the zone of thinning is outside the 1973 extent. The mean cumulative mass balance of the nine glaciers with direct measurements (-10.8 m w.e.) agrees well with the mean change (method B) for the Swiss Alps from DEM differencing (-11 m w.e.) and can thus be considered to be representative for the Alps. Mean thickness change of individual glaciers is correlated with their size, elevation, and exposure to solar irradiation. This implies that mass losses of large glaciers can be underestimated when they are directly inferred from values measured at the generally much smaller glaciers in the mass balance network. Indeed, the mean change with method (A) is only -7.0 m w.e. and thus much less negative than the field derived value. In particular the large regions at low elevations from the largest ice masses contribute to the stronger loss.

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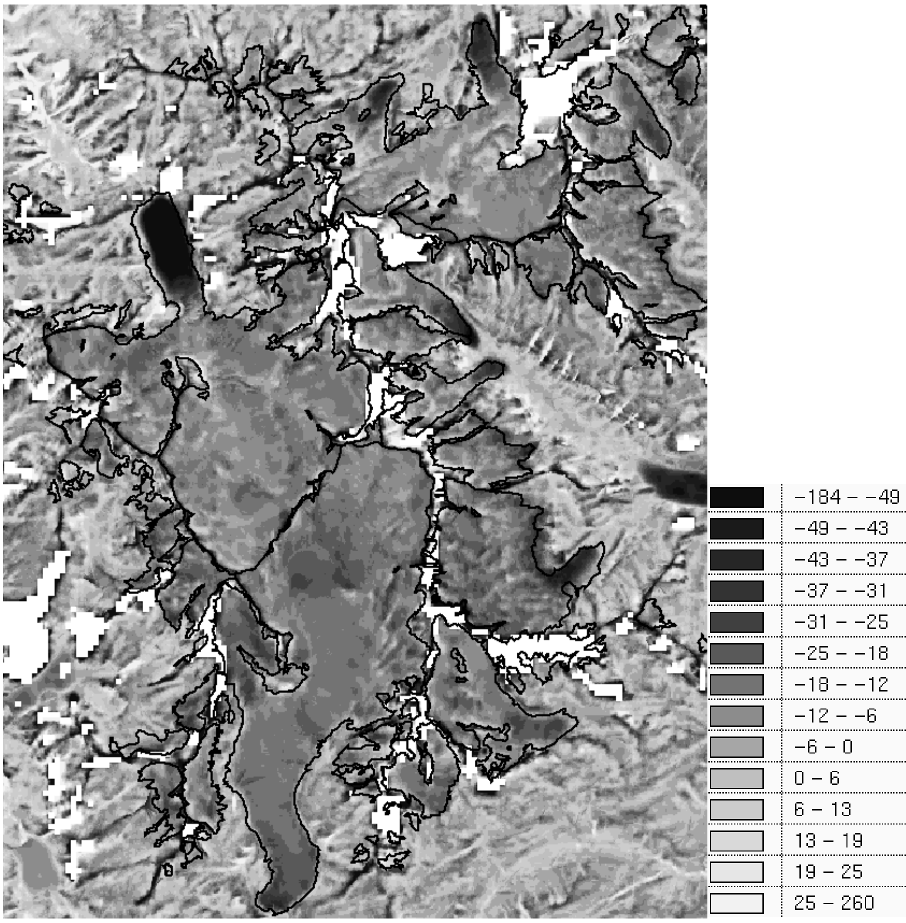

6.22

GlobGlacier: A new ESA project to map the world's glaciers from space

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Changes of glaciers and ice caps are key indicators of climatic change, mostly due to their enhanced and well recognizable reaction to small climatic variations. They have thus been selected as one of the essential climate variables (ECVs) in the global climate observing system (GCOS) and their monitoring is organized in a tiered strategy within the global terrestrial network for glaciers (GTN-G). Within GTN-G, annual measurements of mass balance (c. 50 glaciers) and length changes (c. 550 glaciers) are performed and in the world glacier inventory (WGI) detailed data exist as point information for about 71'000 glaciers, which is c. 40% of the estimated 160'000 glaciers worldwide. Thus, (1) the current sample of glaciers with annual measurements is very small and might be not representative for the changes at a global scale and (2) the WGI is not complete and difficult to use for change assessment (point data). As melting glaciers and ice caps might provide an even larger contribution to global sea level rise in the coming decades than the two continental ice sheets, there is an urgent necessity to generate more complete and representative data sets (GCOS, 2006).

While the large potential of multispectral satellite data for glacier mapping is already utilized by the GLIMS initiative to create a digital database of glacier outlines, the full potential of satellite data for determination of glacier mass balance or length changes in a systematic way remain to be explored. As the required techniques for mapping glacier snow lines, topography, elevation changes or velocity fields (all indicative for mass balance) do already exist, a remaining challenge is their integrated and systematic application to a large set of glaciers (IGOS, 2007). The here presented new ESA project GlobGlacier aims at exploring and applying the existing methods to already archived satellite data in order to contribute to existing databases (GLIMS, WGI) and observation programs (WGMS). GlobGlacier is one of ESAs data user element (DUE) activities that responds to the needs of some major users groups, which are actively involved in defining the products and assessment of the service (Volden, 2007).

The products that will be generated by GlobGlacier include (see Fig. 1): glacier outlines and terminus positions for 20'000 units each, snowlines and topographic information for 5000 units each, elevation changes for 1000 units and velocity fields for 200 units. The techniques to be applied vary with the product and the sensor and include optical and microwave satellite data as well as laser altimetry (cf. Paul et al., subm.). Glacier **outlines** will be derived from multispectral sensors (mainly Landsat TM/ETM+) using well established methods (band ratios with threshold) combined with manual editing and GIS-based data fusion at three different levels of detail: Level 0 (L0): outlines enclosing contiguous ice masses that are corrected for misclassification (e.g. debris, shadow, water); L1: individual glaciers that result from combining L0 outlines with hydrologic divides; L2: outlines from L1 combined with DEM data to obtain a detailed glacier inventory. The **terminus position** will be marked where the central flowline crosses the glacier terminus. **Snow lines** will also be derived from optical imagery based on terrain and atmospherically corrected albedo values. The **topography** information is basically derived from the freely available SRTM DEM and complemented by DEMs from optical stereo sensors (e.g. ASTER, SPOT) and interferometric techniques (e.g. using ERS1/2 SAR data) in regions outside the SRTM coverage. **Elevation changes** will be calculated by differencing DEMs from two points in time and by comparing spot elevations from laser altimeters at orbit crossing points. Finally, **velocity** fields will be derived from feature tracking of repeat pass optical imagery or from microwave sensors using differential SAR interferometry or offset-tracking. The time period analysed will depend on the available satellite data and vary from seasonal to annual means.

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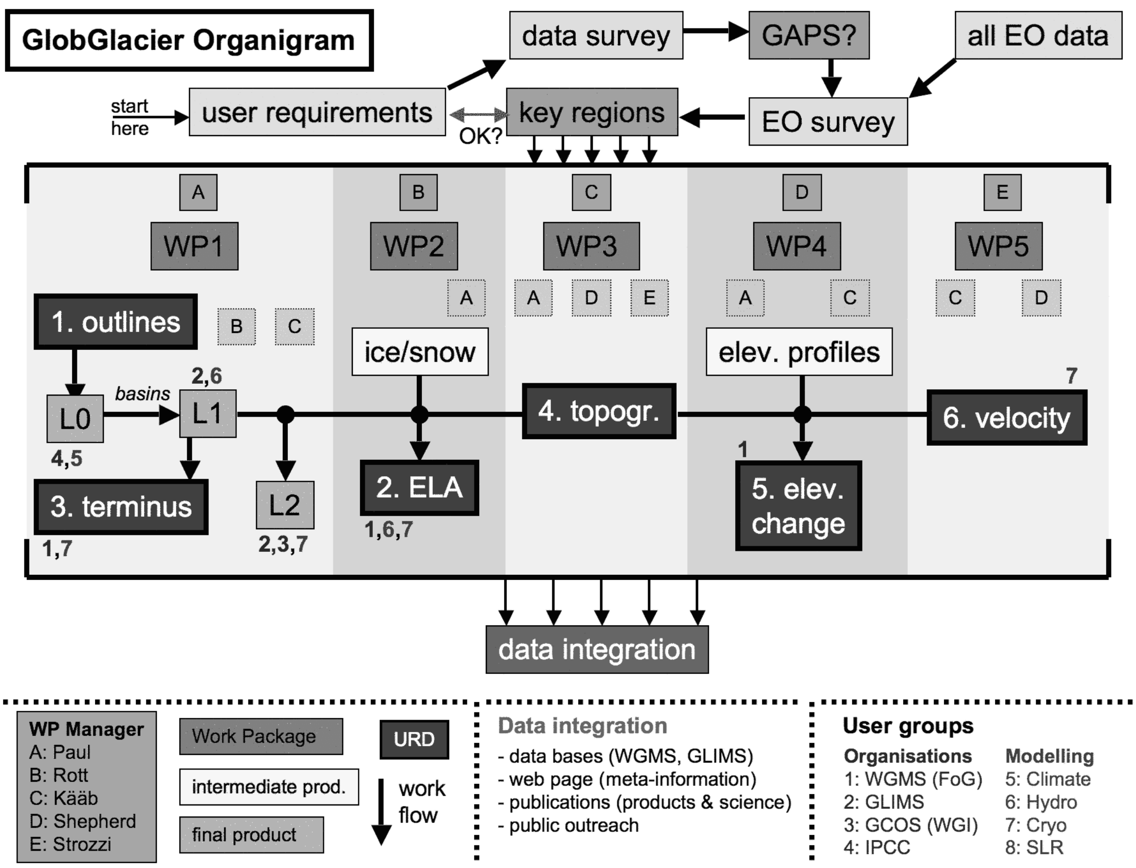

Figure 1. Schematic overview of the workflow, the workpackages and the generated products of the GlobGlacier project.

6.23

Rapid permafrost degradation induced by non-conductive heat transfer within a talus slope at Flüela Pass, Swiss Alps.

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Talus formations are an important type of debris storage in mountain environments and the degradation of ice within them can lead to the triggering of mass movements or to structure instability (Phillips and Margreth 2008). Numerous surface investigations have shown that the inner structure of talus formations and hence the processes occurring there can be complex. However, few direct measurements exist, for example in boreholes. One of the earliest studied talus slopes in the Swiss Alps is a NE oriented, 25-35° slope located at Flüela Pass, ranging between 2380 and 2600 m asl. The slope is bounded by a rock wall at the top and by a lake at the base. Geophysical investigations in the 1970s indicated the presence of ground ice at the base of the slope, thinning upslope and not occurring at the top (Haeberli 1975). The presence of permafrost was attributed to the persistence of avalanche debris at the base of the slope in summer and later also to local differences in surface roughness (Lerjen et al. 2003).

Two 20 m deep boreholes were drilled at the site in 2002, confirming the presence of ice at the base of the slope (Luetschg et al. 2004). Borehole B1 is located at 2501 m asl (midslope) and B2 is at 2394 m (near the base of the slope). Borehole stratigraphies showed the presence of varying amounts of ice between 3 and 10 m depth and the occurrence of coarse blocks interspersed with large voids at 9 – 14 m depth in B1 and at 10 –17 m depth in B2; the material presumably originates from para-/postglacial rockfall deposits or blocky Egesen moraines, which were subsequently covered with firn/ice and finer clasts.

Borehole temperature measurements have been carried out in B1 and B2 since 2002, using 12 YSI 44008 thermistors and Campbell CR10X loggers in each borehole. Meteorological data was obtained near to the slope in a flat area of Flüela Pass. During the measurement period (2002-2007) active layer depths have remained very constant at 3 m, even during the summer 2003 heat wave, pointing to the ongoing presence of ice below 3m. In 2003 the permafrost body in B2 was 7 m thick, between 3 and 10 m depth. By July 2008 its thickness had halved and was located between 3 and 6.5 m depth. This rapid permafrost degradation was triggered from below.

Borehole temperature data also indicate the occurrence of thermal anomalies at around 10 m depth in B1 and around 15 m depth in B2. The temperature curves here display a much higher variability and amplitude than those measured just above and below. This suggests the occurrence of intra-talus ventilation through the large voids within the coarse blocky material, a phenomenon driven by the expulsion of the relatively warmer and less dense intra-talus air in winter, leading to the aspiration of cold external air into the base of the slope (Delaloye and Lambiel 2005). The phenomenon is particularly effective with cold air temperatures and low snow depths and can also occur in summer when air temperatures are below 0°C.

The presence of voids and the evidence of the occurrence of intra-talus ventilation suggest that non-conductive heat-transfer processes, in particular latent heat effects, are contributing to the extremely rapid thinning of the permafrost ice from below. As the intra-talus air is drawn through the snow cover into the voids and because temperature gradient induced vapour migration occurs from below, the intra-talus air must have a high moisture content; when this air comes into contact with the frozen ground and the dew point is reached, condensation will occur, releasing energy and enhancing permafrost degradation. The latent heat of condensation is high (2.5 MJ kg^{-1}), so little vapour is required to cause significant warming.

Further investigations such as gas-tracer experiments, local microclimatological measurements and more detailed borehole temperature measurements will be required to analyze the causes and effects of the intra-talus ventilation in detail. The existing measurements deliver interesting information on possible mechanisms of currently occurring permafrost degradation in alpine talus slopes.

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6.24

Rockglacier dynamics in the Swiss Alps – comparing kinematics and thermal regimes in the Murtèl-Corvatsch region

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In the context of the recent climatic changes and their impact on the cryosphere, permafrost environments play a key role due to their sensitivity towards thermal changes and resulting geomorphological response. The indicative role of rockglaciers in these geosystems was emphasized only recently (e.g., Haeberli et al. 2006), but was up to now mainly restricted to temperature variations within the permafrost body as well as variations in active layer thickness. Within the last decade, an increasing number of studies monitored and quantified the creep behaviour of rockglaciers in the European Alps and observed increasing surface displacements since the 1990s (e.g., Schneider & Schneider 2001, Lambiel & Delaloye 2004, Kääb et al. 2007). In this context it is described, that the Alpine rockglaciers show a rather synchronous behaviour and respond sensitively to recent temperature increase (Roer et al. 2005, Kääb et al. 2007, Delaloye et al. 2008). There seems to be a strong indication that the observations are related to a warming of the shearzone within the individual rockglaciers (Arenson et al. 2002).
The presentation aims at the combined analysis of rockglacier kinematics and thermal characteristics in the Murtèl-Corvatsch region, one of the best equipped permafrost research sites.

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6.25

Electromagnetic Prospecting in Alpine Permafrost: Examples from the Southern Swiss Alps

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Within the framework of geomorphological and glaciological investigations of the Lateglacial and Holocene glacier/permafrost evolution in the Canton Ticino (Southern Swiss Alps), several geophysical methods (frequency-domain electromagnetic lateral mapping and 2D resistivity profiling, direct-current resistivity soundings, self-potential measurements and thermal prospecting) have been used for mapping the permafrost distribution at the local scale (Scapozza 2008; Scapozza et al. 2008). In this context, the application of electromagnetic geophysical methods in the prospecting of alpine permafrost is a recent and not well-developed approach (see, for example, Hauck 2001).

In this study, two frequency-domain electromagnetic methods were used: the field ground conductivity-meter Geonics EM-31 and the VLF-R (Very-Low Frequency Resistivity) resistivity-meter Geonics EM-16R. The Geonics EM-31 operates at a fixed frequency and allows to determine the spatial apparent conductivity and inphase variations in the survey area (McNeill 1980). The inphase is proportional to the magnetic susceptibility of the ground. The depth of investigation depends to the spacing between transmitter and receiver (3.66 m for the EM-31) and to the frequency (9.8 kHz). According to the polarisation of the instrument, the depth of investigations is around 6 m with the vertical dipoles (VD) and around 3 m with the horizontal dipoles (VH). The VLF-R technique uses electromagnetic energy radiated by a very low frequency (VLF) transmitter (Cagniard 1953). In this study the Rhauderfehn transmitter (23.4 kHz) located in Germany (near Bremen) was used. The measurement of the horizontal component of the electric field (E) and of the horizontal magnetic component (H) perpendicular to the azimuth of the transmitting station allows to know the apparent resistivity of the near surface. The ratio between H and E gives a phase angle that changes according to variations of resistivity with the depth. The combined inversion of apparent resistivity and phase angle data allows us to realize 2D VLF-R tomography with a two-layer resolution.

The measurement carried out on the Piancabella rockglacier (Blenio Valley) (Fig. 1A) show that permafrost occurrence is probable, with maximal resistivities at the front of the rockglacier and a decrease of the values toward upslope, as expected by geomorphological observations and other geophysical measurements (see Scapozza 2008). In particular, the electromagnetic prospecting allows us to know approximately the active layer depth and the permafrost resistivity, as shown in the VLF-R tomography (Fig. 1B). This example shows that electromagnetic prospecting in alpine permafrost offers good possibilities to map the spatial apparent resistivity (i.e. the permafrost distribution) (EM-31 and VLF-R) and/or to obtain information concerning the structure of the prospected terrains (VLF-R tomography).

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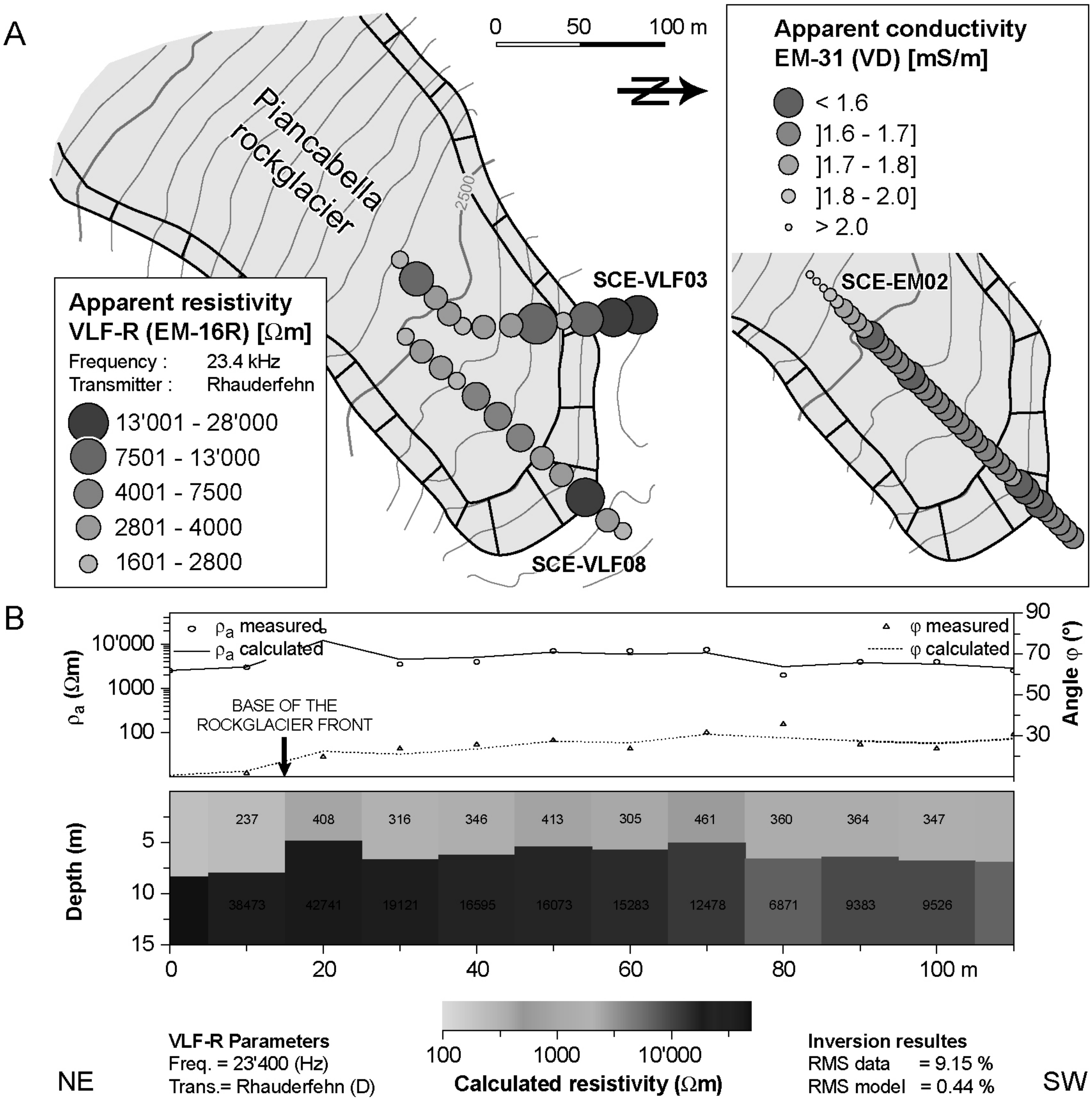

Figure 1. A: VLF-R (EM-16R) and EM-31 profiles along the Piancabella rockglacier. B: VLF-R tomography of the profile SCE-VLF08.

6.26
Permafrost Map of the Eastern Ticino Alps

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The permafrost distribution and characteristics in the Southern Swiss Alps are poorly known because of lack of research dedicated to this morphoclimatic context of the Alps during the last decades. In spite of the interest for the cryosphere reactions to climate warming, only few scientific studies were carried out until now in the periglacial belt of the Ticino Alps. Within the framework of geomorphological and geophysical investigations on the Lateglacial and Holocene glacier/permafrost evolution in the Southern Swiss Alps (see Scapozza & Reynard 2007; Scapozza 2008; Scapozza et al. 2008), a regional model based on an inventory of 75 rockglaciers was developed to simulate the permafrost distribution in the Eastern Alps of the Canton Ticino (Fig. 1). The model used is based on the assumption that the permafrost distribution at the regional scale depends mainly on altitude and orientation (topoclimatic parameters) and that the minimal altitude of active/inactive rockglaciers can be used as an indicator of the lower limit of discontinuous permafrost. The model was calibrated by thermal and geophysical prospecting, in order to asses the permafrost distribution at the local scale. Moreover, several sites were equipped for long-term studies. At the moment, in the Eastern Ticino Alps (Fig. 1), the followings studies are carried out:

- Geomorphological mapping and geophysical prospecting and monitoring in the Sceru Valley. The geophysical prospecting was carried out with frequency-domain electromagnetic lateral mapping and 2D resistivity profiling (Geonics EM-16R and EM-31), direct-current (DC) resistivity soundings, self-potential measurements, and thermal prospecting (miniature ground temperature data loggers and spring temperatures) (Scapozza 2008; Scapozza et al. 2008). On the Piancabella rockglacier and on the Gana Rossa talus slope, a ground- surface temperature and self-potential monitoring network was set up.
- Geomorphological mapping, direct-current (DC) resistivity soundings, ground-surface temperatures and real-time kinematic (RTK) GPS monitoring for studying the dynamics of creeping permafrost in the Northern side of the Cima di Gana Bianca, particularly on the Stabbio di Largario rockglacier (Valenti 2006; Müller, in prep.).
- ERS InSAR (space-borne synthetic aperture radar interferometry) signatures inventory to estimate both magnitude and spatial pattern of slope motion in the periglacial belt of the Ticino Alps, in particular in the Gothard region and in the Blenio Valley.

In the next years, the study and the equipment of others sites for permafrost research and monitoring is planned in the Val Bedretto region and in the Greina region. The goal is to better known the cryosphere reaction to recent climate warming in order to assess and quantify the processes related with permafrost degradation in high mountain environments.

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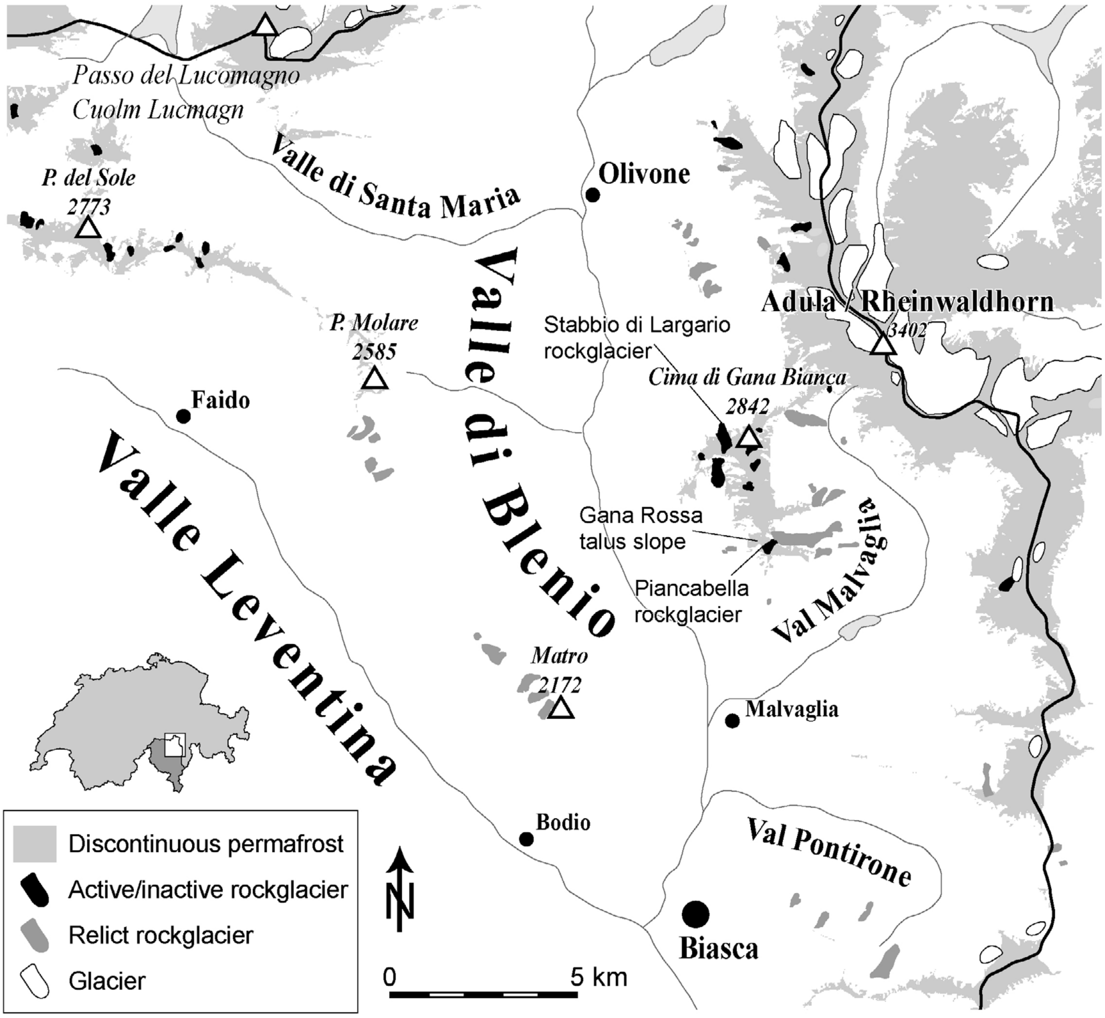

Figure 1. Permafrost and rockglaciers distribution in the Eastern Ticino Alps.

6.27

Conceptualising sediment cascades to enhance dynamic geomorphological mapping

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Research focusing on geomorphological mapping often concerns the establishment of landforms inventories at large scales. The main disadvantage of the maps produced is their static character. In fact, available geomorphological legend systems are not always sufficient for mapping alpine environments with high geomorphological activity. A good example is illustrated by torrential systems where dynamic processes like channelised debris flows occur and where landforms associated to these processes may change very fast in time and space scales. Assessing sediment volumes that supply debris flow channels is one of the key parameters to mitigate disasters on places geomorphologically concerned by fluvial processes (Zimmermann et al. 1997). Data derived through GIS spatial analysis based on high accuracy digital elevation models (slopes, aspect, hydrographic network and delineation of subwatersheds) might be of high interest for mapping dynamic geomorphological processes as shown by an attempt done for Bruchi torrential system in the Swiss Alps (Theler et al. in press). This paper proposes to use GIS tools coupled with a qualitative conceptualisation of the system, what should open new opportunities for geomorphological mapping. An example is presented for a torrential system in the Swiss Alps.

The different parts of the system are conceptualised in order to depict the sediment transfers on a mountain flank (Fig. 1, 2). Sediment transfer starts from the hillslopes (1), where physical weathering followed by gravitational processes are predominant. The time of residence of sediments is very variable depending on the topographic setting and the intensity of processes and could be related to a complex stochastic function (e.g. Hegg, 1997). Sediments may have a second repository when they reach the active gully (2). Here, the time of residence depends on water runoff. It could be explained by less complex functions, because transfer is done only through two processes – debris flow or bed load transport. These two phenomena transfer sediments very actively and therefore do not store them for long (3). When they reach the fan (4) sediments transported by active geomorphic phenomena could either be stored (5) or transit directly to the effluent (6). Following these previous observations debris transfer are then replaced into the global erosion system. This could help to highlight with which part of the system volume assessment model are playing. The global scheme can be summarised by a tank cascade as depicted in Figure 2. The size of the tank is referred to the potential residence time of sediments (the difference in size on the graph must be seen in a logarithm perspective).

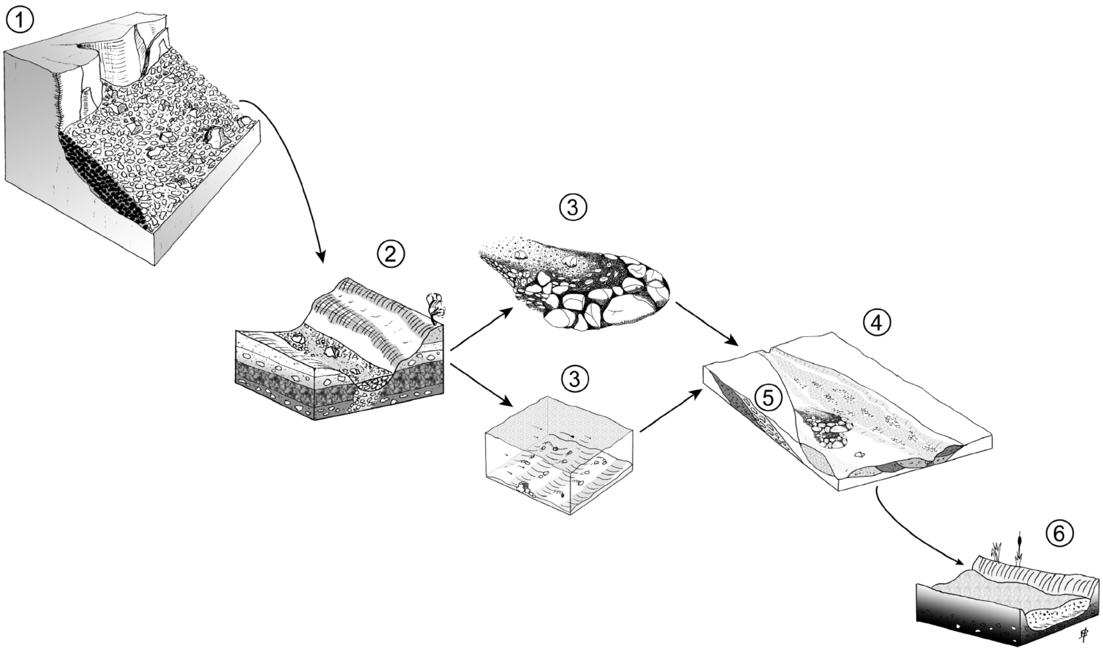

Figure 1. Place of debris flow and bed load transport into the erosive system.

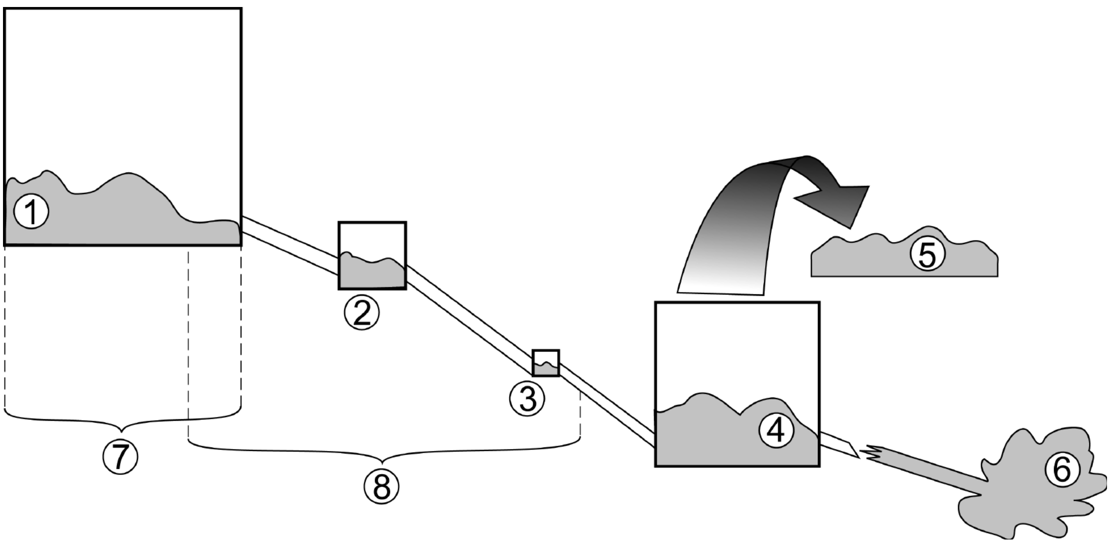

Figure 2. Tank cascade for sediment transfer and landscape elements where the different formula are applied.

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6.28

Glacier volcano interactions and related hazards during the 2007 eruptive crisis at Nevado del Huila, Colombia

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Nevado del Huila, a glacier-covered volcano in the South of Colombia's Cordillera Central, has not experienced any historical eruptions. In February and April 2007 the volcano erupted with two comparably small phreatic events. Each eruption was accompanied by the formation of large fissures in the Huila summit region of 2 km length and 50-80 m width with continued strong fumarolic activity after the eruptions. The eruptions produced lahars that travelled 150 km down the Paez River, with flow volumes of several million m^3 and ≈40 million m^3 for the February and April events, respectively. The water content of the April flow is estimated at ≈25 million m^3.

The eruption and glacier related dynamics were analyzed using air-borne photography, QuickBird and Aster satellite imagery. It was found that glaciers were not affected by the eruptions in a magnitude that would correspond to the amount of ice-melt generated water necessary to produce the observed lahar flow volumes. Instead, indications of flow paths suggested that most of the water that formed the lahars was expelled from the fissures, stemming from hydrothermal water reservoirs. Channels of a few meters depth incised in glacier ice provided evidence of water flow over the glaciers with temperatures likely exceeding 80°C. Sediment was deposited on the glaciers and further downstream. During the April eruption the lowermost part of the El Oso glacier failed, probably as an avalanche with about 0.5 million m^3 of ice. The mechanism that caused this glacier failure is not yet well understood but could be related to hot water released from the summit fissures that entered the base of the glacier and provoked a sudden reduction of shear strength at the glacier-bedrock interface.

The understanding of the volcano-ice interactions on Nevado del Huila and related formation of large lahars is important in view of the resulting severe hazards. The particularly large dimension of the lahars associated with the 2007 eruptions leave space for discussion as to the origin of such large amounts of water. A literature review suggested that drainage of similarly large hydrothermal water reservoirs during eruptive activity is very rare. More investigations are therefore needed to better constrain the relevant processes.
As to the future conditions at Nevado del Huila, it is most likely that glaciers will continue to respond to ongoing atmospheric warming. In the last 20 years glaciers were found to have shrunk by 30% to a current size of 10.7 km^2, with an estimated ice volume equivalent to 410 million m^3 of water. The current rate of retreat suggests glaciers could disappear completely in the second half of the 21st century, and hence still represent a major source of hazard when interacting with volcanic activity resulting large lahars.

6.29

Analyses of newly digitised snow series over the last 100 years+ in Switzerland

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Snow is on the one hand an important commercial factor especially in the Swiss Alpine region (tourism, hydro-electricity, drinking water) and on the other hand responsible for considerable hazards like avalanches. In addition, snow is an excellent indicator to detect climate change. Hence, high-quality long-term snow series are crucial for reliable analyses.
In the presented study 12 Swiss snow series with daily measurements since at least 1910 (one dating back to 1864, cf. Fig. 1) and altitudes between 450 and 2500 m asl have been analysed. The objectives were twofold. First, suitable long-term snow series have been selected, missing data digitized and the entire series quality checked. Second, the long-term snow series

have been used for trend analyses over a time period >100 years. A snow depth reconstruction with the method of Brown and Braaten (1998) using daily new snow, temperature and precipitation as input variables performed well and made it possible to analyse days with snow pack (Fig. 2).

The results show that the snow cover is varying substantially on seasonal and decadal time scales, which is in line with Scherrer (2006). The analyses of the decadal new snow trends during the last 100 years shows unprecedented low new snow sums in the winter seasons (DJF) of the 1990s. The 100 year trend of days with snow pack reveals a significant decrease for stations below 800 m asl in the winter season (DJF) and for stations around 1800 m asl in the spring season (MAM). Similar results were found for seasonal new snow sums. Finally the results of the trend analyses are discussed with respect to the temperature trends.

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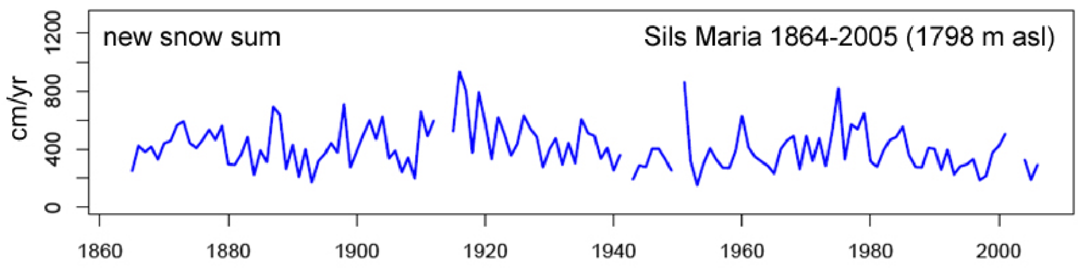

Figure 1. New snow sum series for Sils Maria (1798 m asl) 1864-2005

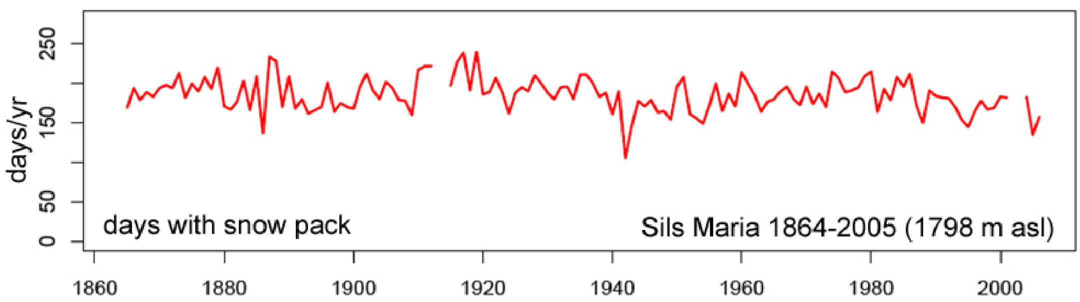

Figure 2. Days with snow pack based on reconstructed snow depth for Sils Maria (1798 m asl) 1864-2005.

6.30

Evidence of warming in disturbed and undisturbed permafrost terrain at Schafberg (Pontresina, Eastern Swiss Alps)

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Both climate and human influences in the form of technical structures may alter ground temperatures in mountain permafrost soils (Phillips 2006). In 1996 several boreholes were drilled into the permafrost of the Muot da Barba Peider (Schafberg) ridge above Pontresina in the Eastern Swiss Alps. This study investigates and compares the ground temperatures measured in two of these boreholes, B1 and B2.

The boreholes are located 50m apart at 2960m asl in a NW oriented steep scree slope and are instrumented with 10 thermistors between 0.5m and 17.5m depth. Both locations are very similar from a climatological and geological point of view. The main difference between the two boreholes is that borehole B1 is located between snow-retaining avalanche defense structures whereas B2 is in the undisturbed scree slope. As a consequence, the snow cover persists longer at B1 than at B2 in early summer, thus modifying ground temperatures there.

11 complete years (1997-2007) of daily borehole temperature measurements at Schafberg (Fig.1) and data delivered by a nearby meteorological station offer a first view of possible influences of climate change and technical structures on permafrost ground temperatures.

For both boreholes, temporal trend analyses show significant warming for annual minimum, mean and median temperatures at depths below 10m and for annual maximum temperatures in all depths. The magnitude of these trends are all similar and at both borehole locations approximately 0.02 – 0.03°C per year, which is less than those registered for example during the same period in Scandinavian mountain permafrost (Isaksen et al. 2007), reflecting the influence of the ridge topography, highly variable snow cover and the presence of coarse blocks at the ground surface at our study site.

Analyses of the maximum annual active layer depth (defined as being the maximum annual penetration of the 0°C isotherm, (Burn 1998)) reveal that the active layer in B2 (around 2m) is almost twice as thick as in B1, due to small local differences in stratigraphy, hydrology and solar radiation (Rist and Phillips 2005). During the 11-year measurement period, the active layer depths in both boreholes have remained quite constant with a temporary deepening during the extremely hot summer 2003. Concerning the annual duration of the active layer, significant positive trends were found for both boreholes. Although the annual duration of the active layer at B2 is about 50% longer than at B1, the increase of the annual active layer duration at B2 (5 days per year) is lower than at B1 (6 days per year).

The comparison of the temporal occurrence of annual maximum/minimum temperature in different depths gives an insight into how fast the ground reacts to seasonal warming/cooling. Cooling in winter occurs similarly at both borehole locations and near-surface warming in summer is delayed due to the presence of the insulating scree cover. Summer warming can additionally be delayed by 1 to 2 months due to the longer lasting snow cover at B1 compared to B2 (e.g. years 1999 to 2001).

In summary, similar warming trends over the period 1997-2007 are visible in both boreholes, indicating the registration of a common warming influence at depth, despite the cooling effect of avalanche defence structures at B1 in summer through the delay of snow melt at the end of snow-rich winters.

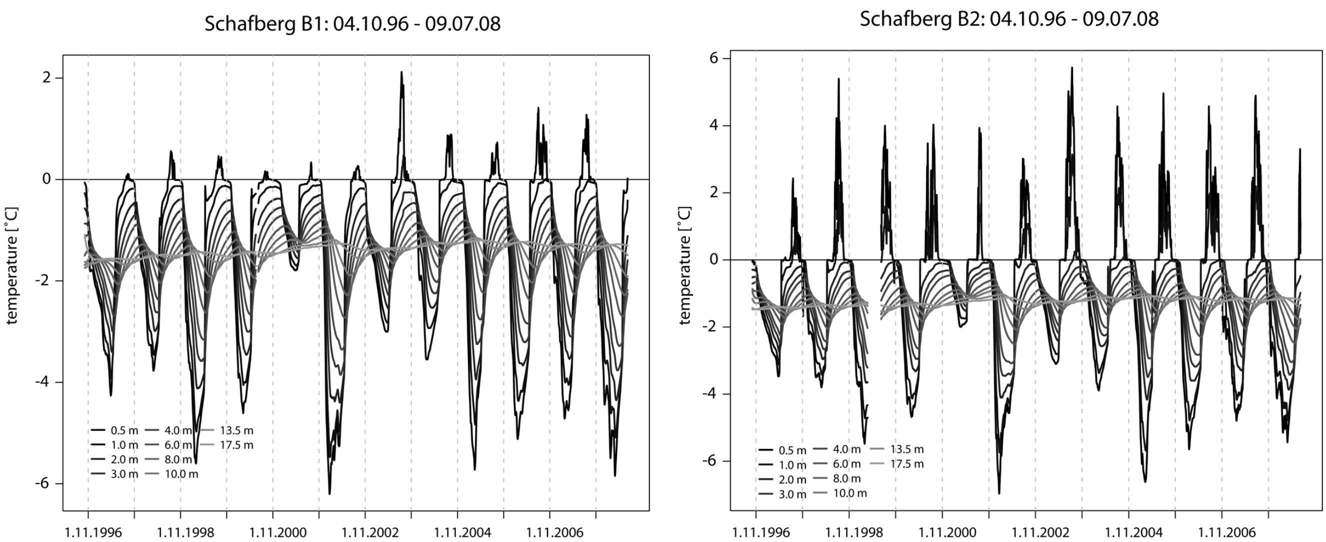

Fig. 1: Ground temperature series in the Schafberg boreholes B1 (left) and B2 (right), 1996-2008

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