Melt Water production due to Strain Heating in Storglaciären, Sweden

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Storglaciären, Northern Sweden, is temperate in most parts except for a cold surface layer in the ablation zone. One of four possible sources for liquid water in temperate ice is melting due to strain heating. An ice flow model was used to calculate velocity fields such that it reproduces surface velocities in close agreement with observed surface velocities. Melt water accumulation is computed by integrating strain heating along trajectories starting at the surface in the accumulation area and ending at the cold-temperate transition surface in the ablation zone.

The distribution of moisture content due to strain heating alone is mapped in a longitudinal section of Storglaciären. Values reach more than 10 grams of water per kilogram ice-water mixture in the lowest parts of the temperate domain. For this moisture content, the rate factor is more than 3 times higher than for water-free ice, and therefore, is important for the modeling of temperate and polythermal glaciers.
Existence of accelerating rock glaciers has been reported by many recent studies (eg. Avian et al. 2005, Roer et al. 2005). Through InSAR (satellite differential Synthetic Aperture Radar interferometry) images and aerial photos analysis as well as field observations, some cases of completely destabilized rock glaciers have been evidenced in the Valais Alps. That is the case for the Petit Vélan rock glacier (swiss coord. 584'000/84'700, fig. 1) and the Pointe du Tsaté rock glacier (608'900/106'500, fig. 2).

Numerous field evidences attest strong recent changes in the rock glacier dynamics: presence of fine grained sediments at the surface of large boulders, tilted blocks with lichen on non exposed faces, existence of large depressed areas downstream well developed scars (fig. 2), while lateral ridges are consequently appearing, etc. The comparison of different terrestrial and aerial photos shows that the changes started generally at the end of the years 1980. Velocities of about 5 m a⁻¹ can reasonably be expected. To describe these completely dislocated rock glaciers, the term of "surging rock glacier" is proposed.

The recent acceleration evidenced coincides with the increase in air temperature since the end of the years 1980. It points to the reaction of creeping permafrost dynamics to changes in climatic conditions. In order to follow the future behaviour of these rock glaciers, a GPS network has been established on the two studied landforms.

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Upscaling is an important issue in ecology allowing quantification and forecasting of ecosystem processes on large and heterogeneous landscapes. A combination of laboratory measurements and spatial data can be used to upscale ecosystem processes measured under controlled conditions in the laboratory.

In this study we investigated respiration of different floodplain habitats and its response to inundation dynamics. Respiration is a key process regulating organic matter stored in ecosystems. Apart from organic matter content and temperature, respiration is largely controlled by changes in water content (inundation).

To test and to upscale the effect of inundation on respiration in an Alpine river floodplain section we combined laboratory experiments and GIS-based modeling. To assess the response of respiration to inundation we immersed sediments from different habitats (gravel, vegetated islands, large woody debris and floodplain forest) with artificial floodwater in respiration chambers. Sediments were collected in a braided section (area 1 km²) of Tagliamento River in NE Italy. This river is characterized by high water level fluctuations. Respiration rates were measured as oxygen consumption for 7 days at 3 different temperatures.

To upscale the experimentally determined respiration rates we used a Digital Elevation Model (DEM) of the floodplain section to simulate inundation dynamics and subsequently the effect of inundation on respiration for the entire floodplain section.
We derived the DEM from oblique aerial images taken at different (0.2-2.6m) stage levels from a nearby mountain top. Images were rectified using Ground Control Points (GCP) assessed by a differential GPS. After rectification we digitized the channel network. All spatial information were combined and interpolated to obtain the DEM. Simulation of inundation dynamics were done by GRID calculation (Fig. 1). In a second step we used the information of the inundation period derived from the GRIDs and the information of the laboratory experiments to predict ecosystem respiration (Fig. 2).

The results showed that small stage variations have a profound effect on inundation and subsequently on respiration activity, creating a complex small scale mosaic of ecosystem respiration in the floodplain river section.

This study demonstrated that the combination of laboratory investigations and spatial GIS data is a useful tool to upscale ecosystem processes in heterogeneous landscapes.

Figure 2. Changes in respiration along a stage level variation in the floodplain section
Example of air circulation and permafrost occurrence in a scree slope in the Swiss Prealps

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Field investigations about the internal circulation of air and the concomitant occurrence of permafrost within scree slope were initiated in 2004 in several sites between 1400 and 2200 m a.s.l. in the Swiss Prealps. First results show that the circulation of air is a mechanism common to all prospected sites (see abstract from Morard & Delaloye). Moreover, permafrost is likely to occur in most cases (according to electrical resistivity measurements) despite a mean annual air temperature (MAAT) between +1 to +4.5°C depending on the elevation.

In this study, we will focus on the site of the combe of Vudêche located downwards the south – east face of the Dent de Lys (canton of Fribourg).

Air circulation throughout an accumulation of loose sediments is primarily controlled by the thermal gradient between the surrounding air and the ground. The flow direction seasonally reverses: to an ascent of relatively warm light air in winter, which favours consequently the penetration of cold air at the base of the debris accumulation, succeeds a gravity discharge of relatively cold dense air during summer. The process leads to a strong annual negative anomaly of the ground temperature in the lower part of the ventilated formation (Delaloye 2004). Our study focuses on a more detailed comprehension of the ventilation mechanism and its implication in the occurrence and preservation of sporadic alpine permafrost. Field investigations prevail: detailed geomorphic mapping, frequent site visits, ground surface temperature and electrical resistivity measurement.

Frequent field visits allow to describe the varying nature and significance of phenomena, that can be observed at the ground surface and associated to both intensity and direction of the air stream in the debris accumulation (e.g. snowmelt window, hoarfrost, basal icing of the snow cover, funnelling, condensation fog, ground icing, aspiration holes). Air circulation appears to be more complex than previously assumed, particularly during the periods when the contrast in temperature is weak with a daily reversibility of the flow direction.

Repeated electrical soundings measurements show a variation of the resistivity in the apparently overcooled ventilated areas of the scree between the end of winter and the end of summer. The resistant layer is located between about 2 and 20 m depth. The resistivity values may be due either to the large porosity or to the frozen state of the sediment or, more probably, to the frozen state of an open-void material.

Performing a BTS (bottom temperature of the snow cover) mapping after a long period of cold weather has revealed to be a valuable method for determining both the efficiency and the spatial extent of a ventilation system acting throughout a debris accumulation even in the presence a thick snow cover. This methods has revealed an overcooled area in the lower part of the scree slopes, an area with ground temperature higher than 0°C in the upper part of the scree slopes, indicating “warm” air outflow. In the middle part of the talus slopes, a rapid transition in the temperature pattern can be observed.

Several data loggers (UTL-1) were placed in the field at the end of July 2004. They recorded ground temperatures (one of them recorded the surrounding air temperature) and have been collected in the beginning of September of this year. These data proved the annual negative anomaly of the ground temperature in the lower part of the ventilated formation as shown in Figure 1. Furthermore, these data would be very useful to precise the thermal regime and the direction of air circulation throughout an accumulation of loose sediments.
Figure 1. The picture shows three curves of temperature taken from three data loggers UTL-1. One recorded the temperatures of the surrounding air, the two others recorded the ground temperatures (in the upper part and lower part of the scree).

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Quantitative assessment of permafrost degradation in steep topography using geophysical monitoring systems

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A climate induced warming of the atmospheric surface layer and a corresponding increase of ground temperatures will lead to substantial changes in the water and energy balance of regions underlain by perennial frozen ground (permafrost). Due to the strong heterogeneity of the subsurface in Alpine terrain, changes in air temperature can not simply be related to changes in ground temperature or melting rates. One of the main problems in the assessment and modelling of the future permafrost evolution is the lack of 3-dimensional information of the subsurface. In addition, the potential instability of a slope depends strongly on the characteristics of the subsurface material like ice content, porosity or crack size/orientation, unfrozen water content and hydraulic properties. As in existing European (Permafrost and Climate in the 21st Century, PACE21) and Swiss (PERMOS) permafrost monitoring networks, subsurface temperature data can be obtained through a network of shallow and deep (down to 100m) boreholes, but due to the heterogeneity of Alpine surface and subsurface characteristics, the temperature data can not easily be generalised for larger areas. Furthermore, difficult and costly logistics of drilling in mountainous environments make an area-wide investigation through a large number of boreholes impossible.

Surface based geophysical methods represent a cost-effective alternative for determining 3-dimensional fields of subsurface properties like ice content, porosity, unfrozen water content and lithospheric material type. Due to the indirect nature of the measurements the structure and processes within the subsurface remain unchanged, which makes geophysical methods very suitable for monitoring purposes. From the large variety of geophysical methods, mainly electric, electromagnetic and seismic techniques have been applied on frozen ground, as the electrical resistivity, the dielectrical constant and the seismic wave velocity exhibit a marked increase at the freezing point. DC resistivity tomography, refraction seismic tomography and ground penetrating radar have been successfully used to detect ground ice in rock slopes, rock glaciers, ice-cored moraines, talus slopes and low-altitude isolated permafrost occurrences (e.g. Hauck & Vonder Mühll 2003, Maurer et al. 2003). In spite of these increasing numbers of geophysical investigations on mountain permafrost terrain, only few efforts have been made so far to use 2-dimensional geophysical information for analysing thermal properties and energy exchange processes between the various layers. Evaluation studies using semi-automatic electric and seismic techniques indicate that subsurface freezing and thawing processes can be detected on time scales of years and even of days and hours (Hauck 2002, Schudel 2003).

In this presentation geophysical approaches to quantify and monitor freezing and thawing processes in Alpine regions are introduced. As the indirect nature of geophysical soundings requires a relation between the measured variable (e.g. electrical resistivity, seismic velocity, dielectric constant) and the respective parts of the material composition (rock, water, air, ice) a new physically-based model was developed, which determines the volumetric fractions of these four phases along a 2-dimensional profile from tomographic electrical and seismic data sets (Hauck et al. 2005).

This 4-phase model is based on two well-known geophysical mixing rules for electrical resistivity and seismic P-wave velocity, Archie’s law and Timur’s equation. In addition to prescribing the material dependent free parameters in Archie’s law, the resistivity and P-wave velocity of the rock material (if present) and the pore water have to be known. Besides, one of the volume fractions has to be explicitely prescribed (usually the porosity). The model was tested
using several electric and seismic data sets from various frozen and non-frozen field sites in mountainous terrain. The results confirm the applicability of the model for various field cases in Alpine terrain. Especially the detection and confirmation of the presence of ground ice was substantially improved. Analysis of the spatial variability of the subsurface, e.g. the detection of isolated air cavities or the differentiation between regions with small and large ice and/or unfrozen water contents, is facilitated, as the two geophysical data sets (resistivity, velocity) are combined to give 2-dimensional profiles of ice-, water- and air content.

In addition, an improved permafrost monitoring approach using repeated seismic and geoelectric data sets is used to calculate the evolution of the ice content at Schilthorn from 1999 to 2005. Ice-, water- and air content are calculated using the above model approach. Results from the 6-year resistivity data set in combination with additional seismic measurements show a decrease in ice content between 1999 and 2004 corresponding to an increase in active layer depth from 5m to 8m as determined from the borehole measurements. The results suggest that geophysical monitoring systems combining different methods may indeed be used to quantify the amount of permafrost degradation as well as its spatial and temporal variability.

Figure 1. Combined geoelectric and seismic measurements along the same survey line on Stockhorn, Walliser Alpen (photograph by C. Hilbich)

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Timing of glacier variations in the central Alps at the Pleistocene/Holocene transition

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The ages and morphology of the Alpine Late glacial moraines record the marked instability of climate at that time and validate the concept that mountain glaciers are very sensitive indicators of climate change. The coherence of our $^{10}$Be exposure age data allow us to examine the fine structure of changes of glacier and rock glacier activity in the central Alps at the Pleistocene/Holocene transition.

The most impressive moraines formed during the Alpine Lateglacial were deposited during the Egesen stadial. In some regions the Egesen maximum (I) moraines occur as a doublet or triplet, in suitable locations many minor moraines are preserved in between (e.g. Maisch, 1987). This indicates a markedly unstable climate, characterized by a succession of glacier-friendly periods (cf. Sailer et al., 1999). Results from the Schönferwall site (Tyrol, Austria), and the outer left lateral moraine at Julier Pass (Lagrev glacier) indicate that Egesen I moraines stabilized between 12'000-12'500 years ago (based on $^{10}$Be). Glaciers in the Alps grew rapidly in response to the drop in temperatures that occurred at the onset of the Younger Dryas, which began around 12'900 yr ago in Greenland ice cores (e.g. Johnsen et al., 2001). At the Julier Lagrev site a second phase is documented by the end region of the inner moraine which shows characteristics transitional between former ice-cored moraine and relict rock glacier. Thus stabilization of the landform was delayed. This second phase dates to about 11'000 years ago.

In some valleys, a moraine set located outside the Little Ice Age limits and much less extensive than Egesen has been recognized. In Kartell valley (Ferwall group, Austria), this stadial dates to between 10'500 and 11'000 years ago ($^{10}$Be). This corresponds generally to the time period termed Palù based on palynological evidence (e.g. Burga, 1987; Furrer, 1991) and is roughly correlative to the Preboreal Oscillation (Johnsen et al., 2001) with a suggested age range of 11'363 to 11'100 in GRIP years. The sum of this evidence implies that in the Alps, the end of the Younger Dryas was not characterized by a sudden jump in temperature. In contrast, rock glacier activity and even advances of small glaciers during the early Preboreal were the response to cold and also rather dry conditions that continued for hundreds of years after the Holocene had begun.

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Differential GPS has proven to be a successful tool for measuring and monitoring the creeping of permanently frozen bodies (e.g. Lambiel & Delaloye 2004). Measurements are carried out on several rock glaciers, frozen Little Ice Age moraine deposits and talus slopes since 2000 for the longest series. In all cases, significant changes in surface velocities have been recorded from year to year.

In the Yettes Condjà valley (Mont Gelé), measurements are carried out every year since 2000 around beginning of September (fig. 1). Rock glacier B displays horizontal surface velocities of about 1-2 m a⁻¹, depending on the year. An insignificant increase of movements was measured between the periods 2000-2001 and 2001-2003 (+4%). Between the periods 2001-2003 and 2003-2004, the change was spectacular: the increase of surface velocities was of 78%. The tendency was then reversed, with a decrease of about 50% between 2003-2004 and 2004-2005. A measurement campaign in July 2005 allowed the seasonally changes for the period 2004-2005 to be evaluated. The decrease in surface movements was of 47% between the periods 2003-2004 and Sept. 2004 – July 2005. The slowing down kept on during summer: velocities July 2005 – Sept 2005 were 21% slower than during winter (Sept. 2004 – July 2005). To resume, a dramatic increase in surface velocities affected the rock glacier between 2003 and 2004, following what a deceleration occurred.

On Becs-de-Bosson/Réchy rock glacier (Delaloye 2004), seasonally (monthly) measurements have been carried out since July 2004. An acceleration (10-15%) was before observed between the periods 2001-2003 and 2003-2004). The velocities stayed high up to January 2005, before suffering of a strong slowing down up to April-May (lowering reaching 50 to 80% of the summer velocities). The horizontal movement increased then again, without however reaching the values of the former summer (fig. 2).

**Figure 1.** Horizontal surface velocities measured on rock glacier B, Yettes Condjà valley (Mont Gelé). The "crisis" of 2003-2004 is particularly well observable.

**Figure 2.** Seasonally horizontal surface velocities measured on Becs-de-Bosson/Réchy rock glacier between 2004 and 2005.
Another case is the Tsarmine rock glacier (Arolla, Lambiel et al. 2004). This landform displays evidences for a recent acceleration of movements, among which frequent destabilisation indices of the rock glacier surface consisting of large blocks largely colonised by lichens. Annual horizontal velocity is about 150 cm a⁻¹. Measurements were carried out in October 2004, June 2005 and August 2005. It was interesting to note that summer velocities (June-August) were 28% slower than the winter velocities (October-June).

Finally, slower movements in 2004-2005 than in 2003-2004 were also measured on the back-moving push-moraine in the Aget glacier forefield (Bagnes valley). A strong acceleration (40-50%) however occurred between 2001-2003 and 2003-2004.

Generally, the changes in rock glacier (permafrost creep) dynamics, that have been measured, are larger than expected before to initiate the measurements. Results show that significant changes may occur at both annual and seasonal interval.

Yearly variations appear to be related to changes in mean annual ground surface temperature with a delay of about one year as attested by the maximal velocities measured in 2003-2004 (in response to both the warm winter 2002-2003 and the heat wave of summer 2003). According to the delay in heat transfer at depth, this confirms that a part (variable from case to case) of the rock glacier (permafrost) creep process occurs at large depth (certainly beneath about 15 m) (Arenson et al. 2002). Annual "crisis" of rock glacier creep may also occur at annual time scale as for rock glacier B in the Yettes Condjà valley.

Seasonal variations may be larger than inter annual variations. They appear to be controlled by ground surface temperature with a delay of a few weeks to several months (on the Becs-de-Bosson rock glacier). Similar observations were reported by Kääb et al. (2003) for the Muragl rock glacier (Grisons). This shows that a relatively large part of the rock glacier (permafrost) creep may occurred in layers close to the surface (less to 10-15 m deep) that are more rapidly and significantly influenced by heat transfer.

Our results also show that a strategy for an adequate monitoring network of short-term variation in rock glacier (and other permafrost features) creep has to be developed.

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Enhancing a distributed mass balance model by a simple parametrisation of snow-redistribution and validation on the example of Bernina group, southeastern Switzerland

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Today’s mass balance models incorporate a sophisticated formulation of the surface energy fluxes. The processes of snow redistribution by wind and avalanches are in most models excluded from the computation. We assume that they are of major influence to the picture of mass balance distribution.

To validate this hypothesis we have developed two distributed mass balance models, one of them includes a simple parameterisation of snow redistribution. We validated the two models on the example of the Bernina group in south-eastern Switzerland. The models are driven by 1999 meteorological data from two meteostations close or within the mountain range. Mass balance distribution for this year was calculated for all glaciers within a DEM of 17km * 13km in size and 25m resolution, including glaciers of different size and exposition. We compared the results of the two models to stake measurements and observed snowlines in 1999, mapped from a Landsat TM scene and from aerial photographs.

Calculated mass balance for 1999 is strongly negative on all glaciers at about -1.2 mwe. Both models are in close correlation with stake measurements on Morteratsch glacier, Bernina group largest valley glacier. When snow redistribution is excluded from the modelling, mean deviation between modelled and observed snowlines is 30 m in altitude and varies from only 7 m in northern to an overestimation of 120 m in southern expositions. Most of remaining 1999’s southerly exposed accumulation zones are believed to consist of avalanche snow. Including processes of snow redistribution confirms this assumption and leads to lower modelled snowlines in southern expositions and also to a generally better correlation of observation and model in the other expositions.

Nevertheless, the model can still not fully explain the complex picture of the snowline. Some modelled deposits of avalanche snow have no counterpart in reality. The spatial distribution of input parameters, especially precipitation, is also assumed to play an essential role on the mass balance distribution. Future work will concentrate on further enhancement of the modelling of snow redistribution, combined with the use of gridded input parameters.
Landslide hazard assessment can be improved by using new digital documents such as digital elevation models (DEM). Geographic Information System (GIS) and geo-referenced documents being more and more available, the geomorphologic theories and methods that were developed before the computer ages are now being updated and improved. They yields new insights for landslide hazard assessment.

Slope processes and associated morphology were extensively studied during the last two centuries (Gilbert, 1880, De La Noe and De Margerie 1888). Terrain slope is the first way to qualify the topography (Strahler 1950) and the basic information used for slope modeling (Young 1972). Terrain slope depends on many factors such as weathering and rock types. In rock slopes, joints play an important role on the slope shaping.

Slope stability is dependent on rock mechanical properties. On one hand, landslides in loose materials (for example in sand piles) are often located within a defined terrain slope angle range. On the other hand, rock slope stability is strongly controlled by discontinuities that decrease rock strength.

Thus, the analysis of topography reflects the mechanical and structural features of the slope. DEM’s make it possible to perform more detailed and systematic morphologic analysis. Using the orientation of each single cell, a DEM can be represented by 3D shaded relief that displays one color for each dip and direction of dip (figure 1). This kind of representation permits a very simple analysis providing quick information for slope hazard assessment, and have shown to be very efficient (Jaboyedoff et al. 2005).

However, although this kind of representation is straightforward with any DEM with specialised software such as COLTOP (Jaboyedoff et al. 2005), it become much more difficult with an unstructured cloud of 3D data points, as a surface must be reconstructed from them. Typically, clouds data points are collected from ground based Lidar.

The main problems which must be solved before performing slope and topography analysis are:

1. Data storage and access, as a typical Lidar survey (scan) can collect more than one million points,
2. Combination of two or more scans within one single set of data points,
3. Triangulation of data points,
4. 3D surface representation according to dip and direction of dip.

The above mentionned points are typical problems of 3D computer graphics and constitute an active research area. Most of them are more or less solved, but the challenge is to integrate them for a specific geological given problem, the main goal being to produce a set of tools which are easy to understand and manipulate (user-friendly) and which can handle very large data-set on current non-specialized hardware. Among these four points, the triangulation
is the most difficult to achieve, because of, firstly, the large amount of data, and secondly the difficulty to perform a triangulation on 3D data. While the first difficulty can be solved by clever data organisation and retrieval, the second can be solved by projecting data points onto a set of plane which roughly approximate the scanned surface. The 3D problem is then reduced into a 2D problem, much easier to handle. Expected results should allow geological scientist for performing very detailed analysis at small scale.

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Evidences of air circulation and permafrost occurrence in talus slopes and relict rock glaciers in the Swiss Prealps

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Investigations about the internal circulation of air and the concomitant occurrence of permafrost within scree slopes and relict rock glacier were initiated in 2004 in three sites between 1’400 and 2’200 m a.s.l in the Swiss Prealps from the canton of Vaud (Bois des Arlettes and Châtillon-Lavaux near the Col-des-Mosses, and la Pierreuse near the ski station of Chateau-d’Oex). First results show that the circulation of air is a mechanism common to all prospected sites. Moreover, permafrost is likely to occur in most cases (according to electrical resistivity measurements) despite a mean annual air temperature (MAAT) between +1 to +4.5°C depending on elevation.

Air circulation throughout an accumulation of loose sediments is primarily controlled by the thermal gradient between the surrounding air and the ground. The flow direction seasonally reverses: to an ascent of relatively warm light air in winter, which favours consequently the penetration of cold air at the base of the debris accumulation, succeeds a gravity discharge of relatively cold dense air during summer. The process leads to a strong annual negative anomaly of the ground temperature in the lower part of the ventilated formation. Our study focuses on a more detailed comprehension of the ventilation mechanism and its implication in the occurrence and preservation of sporadic alpine permafrost. Field investigations prevail: detailed geomorphic mapping, frequent site visits, ground surface temperature and electrical resistivity measurement.

Frequent field visits allow to describe the varying nature and significance of phenomena, that can be observed at the ground surface and associated to both intensity and direction of the air stream in the debris accumulation (e.g. snowmelt window, hoarfrost, basal icing of the snow cover, funnelling, condensation fog, ground icing, aspiration holes). Air circulation appears to be more complex than previously assumed, particularly during the periods when the contrast in temperature is weak with a daily reversibility of the flow direction. Furthermore, connections in the air flow exist between scree slopes and relict rock glacier located underneath (observed in the Bois des Arlettes). In the same way, several ventilation systems located one beside the others can exist simultaneously and apparently independently, as observed in the Pierreuse area.

Several electrical resistivity measurements systematically show the presence of high resistivity layers (20-150 k\(\Omega\)m) in the apparently overcooled ventilated areas and in the mass of fallen rocks in the Pierreuse and Bois des Arlettes areas. In the relict rock glacier and, the values vary between 15 and 40 k\(\Omega\)m. The resistant layer are located in each case between about 2 and 20 m depth. In the third investigation site, the Châtillon-Lavaux combe, the resistivity layers show smaller values (3-15 k\(\Omega\)m), probably because of a different geological configuration (more fine rock components). The high resistivity values may be due either to the large porosity or to the frozen state of the sediment or, more probably, to the frozen state of an open-void material.

Performing a BTS (bottom temperature of the snow cover) mapping after a long period of cold weather has revealed to be a valuable method for determining both the efficiency and the spatial extent of a ventilation system acting throughout a debris accumulation even in the presence a thick snow cover. This methods has revealed an overcooled area in the lower part of the scree slopes and in the rooting zone of relict rock glacier, an area with ground temperature near or higher than 0°C in the upper part of the scree slopes, indicating “warm” air outflow. In the middle part of the talus slopes, a rapid transition in the temperature pattern can be observed in all investigated sites.
Several data loggers (UTL) were placed in the field in the last week of September 2004. They recorded ground temperature and will be collected after one year. These datas would be very useful to precise the thermal regime and the varying nature of air circulation throughout an accumulation of loose sediments (see abstract from Dorthe & Delaloye).

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Figure 1. The picture shows the BTS map for the Bois des Arlettles investigation site. 185 measurements were made during February 2004.
A temperature-dependent reduction in rock-wall stability in alpine permafrost areas, likely induced by changes in atmospheric conditions, has recently been demonstrated both in theory and laboratory experiments (Haeberli et al. 1997, Davies et al. 2001). Most instabilities are expected from warm permafrost areas, which is supported by a study of the thermal conditions of starting zones located in permafrost (Noetzli et al. 2003). The hot summer of 2003 provided additional strong evidence for the relation of rock fall and climate change via permafrost thaw.

The delineation of the locations of sensitive zones that exhibit critical temperature changes (entering a range of ca. -1.5 to 0 °C) and are subjected to thaw requires knowledge of the temperature distribution both at the surface and in the subsurface of rock walls. The effect of complex topography in high mountain areas leads to a strong lateral component of heat fluxes (Gruber et al. 2004).

Therefore, ground temperatures and permafrost degradation below variable topography such as ridges, peaks or spurs can only be investigated where 2- and 3-dimensional effects (geometry and variable surface temperatures) are accounted for. The Matterhorn rock fall on July 15, 2003 is an example of such a situation. The starting zone is located in a steep NE-ridge. The corresponding knowledge, however, still remains limited.

In order to investigate 3-dimensional thermal responses to climate change, numerical modelling experimentation is carried out in a recently started study. To better understand natural complex situations, model simulations of typical test cases are performed: In a first step and presented in this contribution cross sections of various idealised 3-dimensional geometries are explored to describe the distribution of ground temperatures under influence of high-mountain topography.
Figure 1. Modelled ground temperatures in the subsurface of an idealised east-west (left) and a north-south (right) trending ridge. The elevation ranges from 2500 to 3500 m a.s.l. and the slope is 60°. The topography influence leads to near-vertical isotherms and a strong lateral heat flux from the warmer to the colder side of the ridge.

The thermal regime inside ridges, peaks or spurs is modelled with varying topographical variables such as slope, aspect or elevation aiming at identifying zones of warm permafrost with critical temperature ranges as well as the position and depth of the degrading boundaries of the permafrost body.

The experimentation is conducted applying a surface energy-balance model (TEBAL, Gruber 2005) to determine surface temperatures, together with a 3-dimensional ground heat-conduction scheme (FRACTure, Kohl & Hopkirk 1995), both especially designed for use in complex topography. Surface temperatures are calculated based on 10years of meteorological data from Corvatsch, Upper Engadine (1990-2000). Finite-element meshes of typical topographies are then generated and forced with the TEBAL-output as surface boundary conditions.

Areas found to be especially sensitive for permafrost degradation may be identified on maps and in the future serve as a basis for hazard assessment of permafrost related slope instabilities.

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Simulations of alpine permafrost scenarios using a one-way coupled RCM – impact model

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High-mountain environments in general and the alpine cryosphere in particular, are affected most seriously by climate change (e.g., Haeberli and Beniston, 1998). The hazard potential of slope instabilities such as rock falls or debris flows is strongly related to changes in the thermal regime of high-mountain environments. Therefore, the modelling and locating of potentially hazardous areas due to climatic changes is an urgent need, especially in densely populated mountain areas such as the European Alps.

In order to simulate the distribution and evolution of ground surface temperatures (GST, an indicator for the occurrence and absence of permafrost) in topographically complex high-mountain regions, the process-based model TEBAL (Topography and Energy BALance) has been developed (Stocker-Mittaz et al. 2002, Gruber et al. 2004). TEBAL simulates the energy fluxes between the atmosphere and the ground surface based on daily meteorological input data. It is well-suited for modelling the impact of climate change on mountain permafrost. However, to date, the model has only been driven with past and current climate data sets. Scenario simulations have only be done in the form of simple ad hoc scenarios.

The most seminal tools for simulating climate scenarios are General Circulation Models (GCMs). However, the horizontal resolution of a GCM (order of 300 km) is not able to explicitly describe the spatial distribution of the climate variables for a local site in areas of complex topography such as the Alps. Therefore, in such environments, the technique of high-resolution regional climate modelling (RCM) is required (Frei et al. 2003). RCMs are driven at their lateral boundaries by GCMs or reanalyses (global analysis of the state of the atmosphere such as ERA-40 or NCEP/NCAR) for selected time slices of the global model run. They reach actually a horizontal resolution of around 20 – 50 km for time slices of a few decades, as required for climate change studies. The vertical resolution is thus reduced too and reaches for example a maximum elevation of the European Alps of around 2200 masl. Therefore, in order to use the output of RCMs for alpine permafrost models which operate at a spatial resolution of about 25 m, a pre-processing of the RCM output is required considering the specific climate conditions at the location of interest.

In this contribution, we present two possible approaches referred to as DELTA- and BIAS-approach that enables us to use RCM output for the simulation of alpine permafrost scenarios (Salzmann et al. subm.). The two approaches are then applied to calculate several scenarios of GST changes for the area of Corvatsch (Upper Engadin, Switzerland). For that purpose we applied output from different RCMs, which were in addition forced with different SRES scenarios. The study shows that the data of RCMs offers new and promising perspectives also in the field of high-mountain permafrost modelling. Due to the fast progress in the development of regional climate models, data with even higher resolution and accuracy which cover many parts of the world will be available in the near future.

REFERENCES


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