Abstract Volume
10th Swiss Geoscience Meeting

Bern, 16th – 17th November 2012

11. Cryospheric Sciences

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Swiss Academy of Sciences
Akademie der Naturwissenschaften
Accademia di scienze naturali
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11. Cryospheric Sciences

J. Alean, A. Bauder, B. Krummenacher, J. Nötzli, C. Lambiel, M. Lüthi,
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Swiss Snow, Ice and Permafrost Society

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11.1
Continuous monitoring of near-surface damage in a freezing rock-wall

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The formation of ice within rock is believed to be an important driver of rock damage near the surface and up to several meters depth. In steep terrain, this process may be crucial for the slow preconditioning of rock fall from warming permafrost areas. Large thermal gradients than can occur close to the rock surface can yield thermal stresses that are also a potential source of damage.

So far most knowledge about these processes stems from theoretical studies or laboratory experiments. However, the transfer of corresponding theoretical insight and laboratory evidence to natural conditions characterized by strong spatial and temporal heterogeneity is nontrivial.

In order to address this problem we have developed a measurement system to investigate in-situ rock damage using acoustic emissions, rock temperature and liquid water content. The measurement system has been deployed on a rock-wall at Jungfraujoch, at 3500m.a.s.l. in the central Swiss alps, and has been continuously monitoring for a year-long period.

The results suggest that frost damage occurs (i) on a wide range of sub-zero temperatures, rejecting the concept of a frost cracking window proposed in previous studies, (ii) with intermittent dynamics (i.e. it is not a continuous process), and (iii) with a strong dependance on the local water saturation level of rock.

11.2
On the sensitivity of different mountain permafrost occurrences to climate change

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To evaluate the sensitivity of mountain permafrost to climatic changes and to assess its future evolution, not only climatic variables such as air temperature, radiation and timing and duration of snow cover, but also subsurface characteristics such as ground ice content, porosity or hydraulic properties have to be considered. In general, simulations with physically-based coupled heat and water transfer models for the subsurface (in the following referred to as 'pf-model') can be used to investigate the impacts of climatic changes on permafrost on the local scale of specific field sites. Using observed atmospheric and subsurface data for calibrating the pf-model one can simulate the evolution of ground temperature, ice content and the future variability of the depth of the active layer by forcing the pf-model with plausible future time series taken for example from Regional Climate Models (RCMs) downscaled to a specific location (Engelhardt et al. 2010, Scherler et al. submitted).

In order to transfer these site-specific results to the sensitivity of different mountain permafrost landforms in general, it is necessary to determine the permafrost conditions, which are most susceptible to (for example) degradation in the context of climatic changes, i.e. radiation, air temperature and precipitation changes. The "permafrost conditions" mentioned above may hereby comprise subsurface variables such as ground temperature, ice content, active layer depth, porosity, thermal and hydraulic conductivity of the host material, but also topographical factors such as slope angle and altitude.

Starting with 100-year projections from combined RCM-permafrost model simulations for two different permafrost sites in the Swiss Alps, we will focus in our contribution on the dominant influencing variables at mountain permafrost sites that determine whether a specific site is endangered to rapid permafrost degradation or exhibit a more stable thermal regime. Additionally, observations from various field sites are used to analyse further permafrost landforms and surface characteristics (Isaksen et al. 2011, Schneider et al. 2012). The sensitivity is hereby quantitatively expressed as the amount of active layer deepening per year per %-change of the respective variable, e.g. air temperature change. Alternatively, a multiple linear regression between active layer depth and the various influencing factors can be performed to find the dominant variables, at least in a statistical sense (Scherler et al. submitted).

The results indicate that the evolution of summer temperatures are dominant for high altitude stations with long-lasting snow cover and low ground ice contents, whereas autumn/early winter temperatures and the specifics of the snow cover evolution are dominant for sites at lower altitude and with smaller snow cover thickness. Coarse blocky sites have usually higher ice contents and are less sensitive to climate changes due to the combined effect of thermal insulation by the air voids in the ice-free near-surface layer and of the energy sink through increased demand of energy for the melting of the high ice contents in the permafrost layer. Consequently, for the currently projected future climate in Switzerland as simulated by RCMs from the EU-Ensembles programme, largest increases in active layer thickness may be expected for fine-grained (or low-porosity), low-ice content sites with substantial snow cover and without the presence of a surficial blocky layer.

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11.3

Intermittent snow drift - experimental study and analysis

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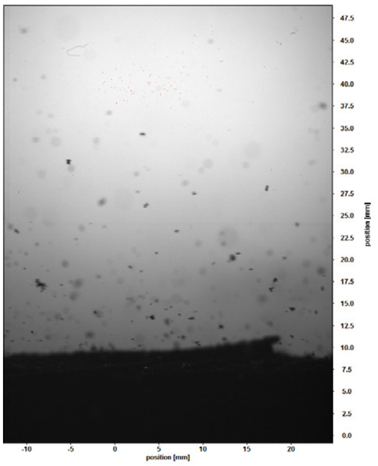
Snow drift due to wind is important and has been studied for many years, for example Clifton et al. (2006), who studied threshold wind speeds for snow drift, or Gordon & Taylor (2009). The redistribution of snow by wind has been shown to be important for small scale snow variability in the alps (Mott et al. 2010) and also has an impact on the mass balance of sea ice.
After several experiments with a particle counter type measurement technique a two-dimensional high speed imaging system was installed in the SLF wind tunnel in Davos. The drifting particles are illuminated with a bright lamp and the camera is positioned so that the shadows of those particles are recorded. An example image with size 30 mm × 50 mm is shown in figure 1a.
This technique was used to study drift of fresh naturally fallen snow by recording 10 images with separation of 0.3 ms. These sets were recorded every 2 s. Therefore it was possible to detect particle size (based on equivalence diameter), velocity and the total particle mass flux at a rate of 0.5 Hz with the software DAVIS (LaVision).

a)



b)

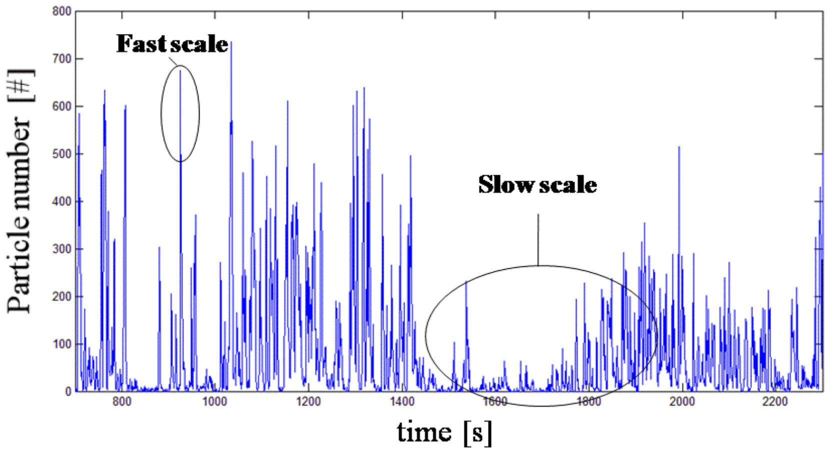


Figure 1. a) Shadowgraphic image (original size . b) Time series of particle number per image.

Figure 1 b) shows distinct peaks in the number concentration of particles approximately one order of magnitude larger than the mean value were observed. Since snow behaves different than solid spherical particles, one set of experiments was conducted with sand, which did show much less pronounced peaks with maximum values a factor three larger than the mean.

These maximum drift events have a duration of less than 10s. An analysis of the dynamics was performed and found that there is a negative correlation of particle streamwise velocity and particle mass flux, indicating the momentum coupling of snow mass flux with the wind. Inspection of the films showed that small structures as in figure 1 a) grow and finally break and a large number of particles is released instantaneously. This intermittent behavior might have important consequences for the modeling of total snow mass flux, since the momentum coupling between wind and particles is highly non-linear.

An additional variation of drift had been observed also on a much slower scale of the order of 5 min, see figure 1b), which shows that the drift becomes very low and becomes larger again. On a beach, Davidson-Arnott & Bauer (2009) have observed that sand particles had to be dried first before removed at a considerable rate, leading to increased sand flux with time. Hence, in our experiment the bonding between that particles could create a drift pattern which shows increased drift after elapsed time of several 10 min. To support this suggested mechanism, we estimated the surface sublimation rate by assuming a fully developed boundary layer flow (relative humidity during the experiment was 77%) which results in reduction of bond size by a factor of two within the order of 10 min. Hence, this estimate indicates that the changing bond size between single snow particles could lead to strongly time dependent drift rates at a slow scale. To clarify this, experiments with (nearly) saturated air are planned in the wind tunnel for the coming winter season.

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11.4

A fiber bundle damage model for viscoelastic ice

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We consider a damage model for viscoelastic ice which is inspired by the widely-used fiber bundle approach. Starting from a one-dimensional model, we develop a multiaxial constitutive model. Viscous deformation is considered as an intermediate configuration in addition to reference and present configuration, which are all three embedded into vector spaces by a local-convected approach. This allows to consistently define the delayed-elastic deformation as the local displacement between viscous and present configuration, and damage as a function of it. Furthermore, we briefly discuss thermodynamic aspects of our theory.

11.5

Storage and release of persistant organic pollutants (POPs) from glaciers

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Glaciers accumulate solid precipitation in form of ice, and with it materials ranging from chemical species to dust and stones. Only under steady climate conditions the release rate of these materials, and water, is constant. Under a varying climate there exist cold periods with reduced release of accumulated water and chemical species, as well as warm periods when water is released at high rate. During the warm periods, high concentrations of chemicals and sediments are released from the glacier. We present results from a transient glacier model which allows us to quantify these processes. In case studies for Oberaargletscher and Silvrettagletscher we show that persistent organic pollutants (POPs) emitted to the atmosphere in the 1950-1960s were stored in the glacier and are released at high rate during the last decade. Consequently, the concentration of toxic POPs in the proglacial lakes are as high as during the time of atmospheric impact, which agrees with measurements in sediment cores.

11.6

Future sea level rise contribution from Greenland's local glaciers and ice caps; the impact of predicted high Arctic precipitation changes.

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Glaciers and ice caps (GIC) on Greenland have yet received limited attention, mainly because a complete glacier inventory was missing until recently. According to the new Greenland glacier inventory published by Rastner et al. (2012) local glaciers and ice caps cover an area of ~89000 km2, about 1.5 to 2 times the values of previous estimates.

Based on the new inventory we calculated future sea level rise contribution (2000-2098) from surface mass balance of all of Greenland's GICs using a simplified energy balance model which is driven by two different climate scenarios from the regional climate models HIRHAM5 (forced from ECHAM under the A1B scenario) and RACMO (Hadgem2-forcing under RCP4.5 scenario). Glacier extent and surface elevation are modified during the model run and mass balance as well as glacier surface change is calculated on a 250 m resolution digital elevation model. Yielding unprecedented level of detail in the modelling of very large glacier samples, this ensures that important feedback mechanisms such as the influence of changing surface elevation on mass balance are considered.

Mass loss of all Greenlandic GICs by 2098 is calculated to be 2050 Gt with HIRHAM5 forcing and 2650 Gt using RACMO. This corresponds to a total contribution to sea level rise of 0.59 or 0.76 cm by the end of the century. The calculated rates in mass loss are nearly identical to observed 2003-2008 values (Bolch et al., subm). However, in contrast to the observations, the modelling does not yet address dynamical mass loss from calving. Total mass loss of Greenland's GICs by 2098 is thus likely to be larger when calving loss is considered.

For the north-east of Greenland it is shown that increasingly negative summer mass balances are largely compensated by a distinct increase in precipitation. Thus glaciers change their characteristics towards greater activity and mass turnover; an observation of considerable importance to modelling efforts of glaciers and ice caps. Modelled future glacier mass balances in the southern half of Greenland are dominated by increasingly negative summer mass balances with no significant change in winter mass balance. HIRHAM5 and RACMO forcing both indicate a similar pattern of precipitation change over Greenland, possibly related to the forecasted continued decrease in Arctic sea ice cover.

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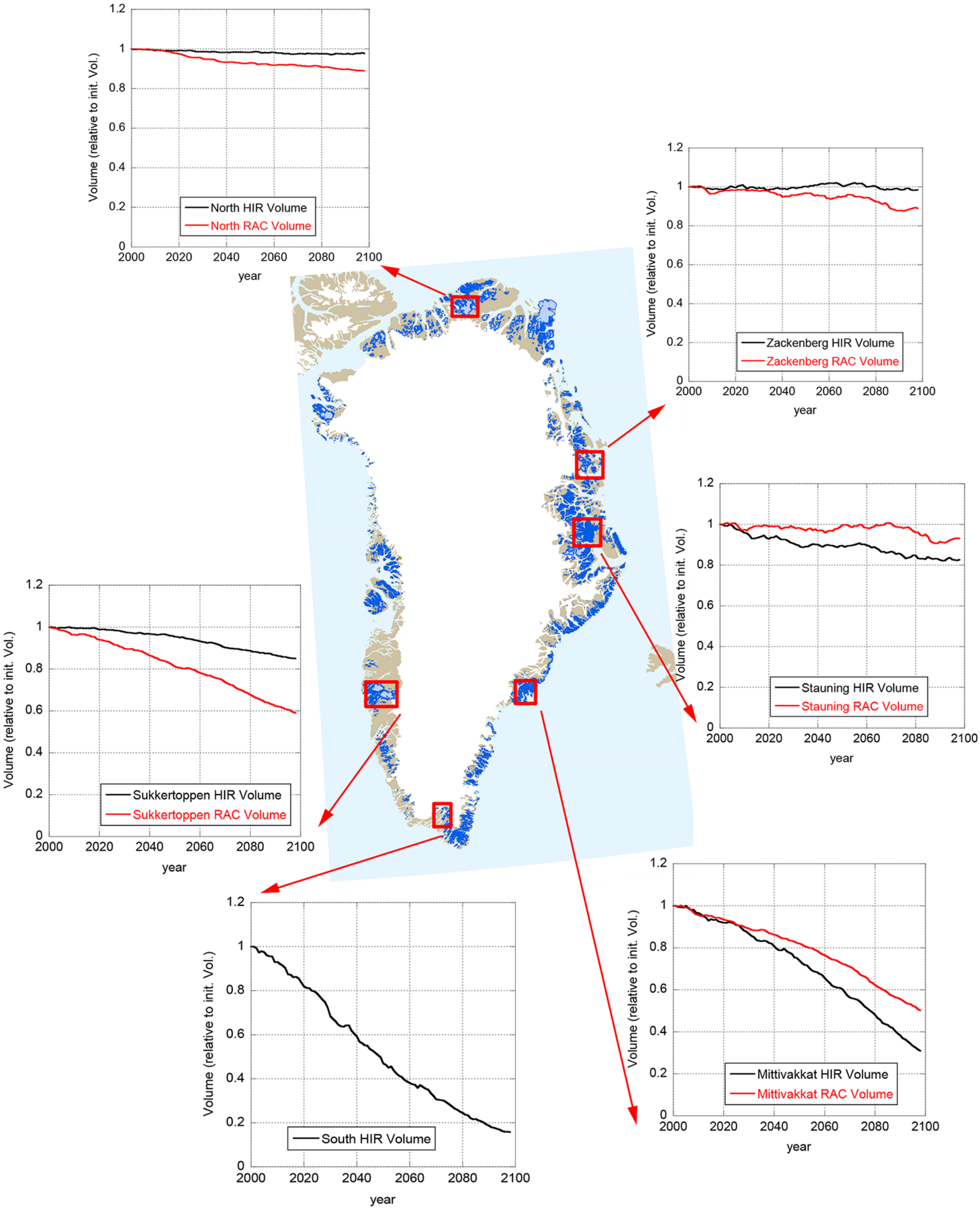

Figure 1. Volume change relative to the initial volume for six selected regions. The applied RCMs are abbreviated with HIR (HIRHAM) and RAC (RACMO) (Figure modified from Machguth et al., subm.)

11.7

Monitoring of Ice Sheet Dynamics in Greenland Using Seismological Techniques

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The Greenland ice sheet contributes about 0.67 mm per year to global sea level rise (Spada et al., 2012). In order to project trends in ice sheet mass balance into the future, interaction between changes in surface melt and ice flow has to be reliably modeled. In this context, a profound understanding of subglacial drainage system is crucial, since its influence on basal motion are critical for ice sheet dynamics (e. g. Zwally et al., 2002; Bartholomew et al., 2010; Sundal et al., 2011).

In order to investigate controls on basal motion, influence of melt water, and subglacial drainage system, the ROGUE[1] (Real-time Observations of Greenland's Under-ice Environment) project was initiated as an international collaboration between ETH Zurich and several institutes in the US. Combining in-situ measurements with numerical modeling, the main project goal is to analyse the drainage system of the Greenland ice sheet and its influence on the dynamics of ice flow. The two main field study sites were located in Western Greenland's ablation zone near Swiss camp, some 30 km north of Jakobshavn Isbræ.

The main field component of the ROGUE project consisted of the 2011 deep drilling campaign and subsequent borehole instrumentation to monitor englacial deformation and temperature as well as subglacial water pressure. Additionally, GPS instruments measured surface flow velocity, while atmospheric and melt conditions were monitored with an automatic weather station and pressure sensors in surface streams and a prominent moulin.

For the duration of 1.5 months a passive seismic network complemented the glaciological point-measurements with the main goal to monitor englacial dislocation sources down to glacier bed. The network consisted of 17 stations including 11 short-period (1 Hz) seismometers at the surface, 3 short-period (8 Hz) borehole sensors (150-350m deep) and 2 collocated broadband seismometers.

The seismic monitoring produced a rich data set including waveforms of icequakes from within the ice sheet and from surface crevasse formation, iceberg calving from nearby Jakobshavn Isbræ, and water-induced tremor.

In this presentation we focus on seismic signatures of englacial water transients and hydrofracturing. These signals are particularly interesting in view of the englacial and subglacial drainage system and its capability to adapt to changes in surface melt. Specifically, we report long-term (>1 hour) tremors induced by englacial water flow during the afternoon hours of days with high melt rates (Figure 1). The tremor signals exhibit different intensities throughout the network indicating a source location near a major moulin. Centered around 4 Hz, the tremor frequencies undergo minor variations, which correlate well with recorded water level in the moulin (Figure 1). We plan to study tremor frequency spectrum in more detail to reveal geometry and temporal evolution of englacial water-filled cavities and conduits.

Finally, we report on icequakes as strong evidence for hydrofracturing at around 100 m depth near the tremor-generating moulin. The icequake shows a typical impulsive, high-frequency (>30 Hz) onset and is followed by a brief 4 Hz tremor signal. As this is close to the frequency of the long-term tremor, we suggest that both water passage as well as hydrofracturing stimulate resonance of the same or similar water-filled englacial channels.
Our results demonstrate that investigations of ice sheet seismicity ideally complement conventional glaciological and geophysical measurements.

[1] http://www.ig.utexas.edu/people/staff/gcatania/rogue.html
http://www.vaw.ethz.ch/people/gz/luethim/projects/data/gz_rogue_seismic

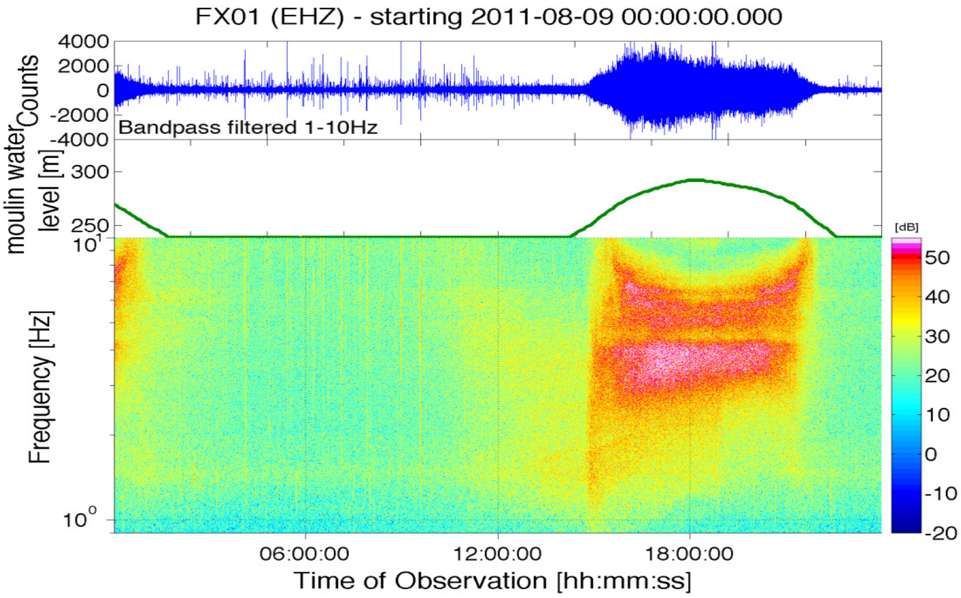

Figure 1. Spectrogram (bottom,unfiltered) and waveform (top, bandpass filtered 1-10 Hz) of the vertical component of the seismic signal during 24h of observations for a 1Hz LE-3D seismometer. The moulin water level (middle) correlates with the occurrence and shape of the seismic tremor.

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11.8

Tracking wetting of a snowpack using upward-looking ground-penetrating radar

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Percolating melt water combined with snow stratigraphy are thought to be the dominating drivers for the formation of wet-snow avalanches. It is, however, difficult to model or measure water flow in a sloping snowpack. For modeling, results highly depend on the type and availability of input data and the parameterization of the physical processes; in the case of sensor deployment, problems with snow gliding and avalanches will arise. In addition, if sensors are placed within the snowpack they will influence the flow of water. Radar technology allows scanning the snowpack non-destructively and deducing internal snow properties from its signal response. If the radar is buried in the ground, it cannot be destroyed by avalanche impact or snow creep.

During the winter seasons 2011-2012 we recorded continuous data with an upward-looking pulsed radar system (upGPR) operating at a frequency of 900 MHz which was placed next to a well-known wet-snow avalanche path. At the same time, we recorded the avalanche activity by observing the avalanche path with time-lapse photography.

We showed that it is possible to operate a solar-powered radar system in a remote site under harsh conditions. Following the signature representing the transition from dry to wet snow, we successfully monitored the advance of percolating water. We determined the bulk volumetric liquid water content and tracked the position of the first stable wetting front. Concurrent wet-snow avalanche activity tended to be high when the water penetrated deeper into the snowpack. Avalanches released when the wetting of the snow reached the bottom of the snowpack. This correspondence suggests that improving the prediction of wet-snow avalanche activity with the help of remotely operating upGPR systems buried in representative starting zones might be feasible.

11.9

Measuring and understanding winter mass balance and snow depth distribution on alpine glaciers from LiDAR DEM differentiation, GPR and snow soundings

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End-of-winter snow distribution is the key factor for the winter mass balance of alpine glaciers and is thus fundamental for understanding and modelling glacier changes. Measuring the winter mass balance using the direct glaciological method provides point measurements only. A better understanding of processes controlling deposition and redistribution of snow, however, requires spatially distributed information on snow depth and its variability. In this study we present simultaneous measurements from 2010 using not only the glaciological method but ground penetrating radar (GPR) and Light detection and ranging (LiDAR) digital elevation models (DEM). Our study site is Findelengletscher, Valais, Switzerland, a large alpine valley glacier (13.4 km^2).

The glaciological survey provides snow depth data from 463 soundings and density measurements at 13 snow pits across the glacier (Figure 1). Spatially distributed snow depth and snow water equivalent are gained through extrapolation in the same way as it is done when using the glaciological method for mass balance evaluation.
Differentiation of LiDAR DEMs (Joerg et al., in review) has previously been used to assess snow depth distribution. Usually,

the influence of the vertical component of glacier flow is neglected. In the case of Findelengletscher, however, this leads to a strong misfit with glaciological in-situ measurements. The required correction is based on the 5-year mass balance record and observed geometry changes. This estimation of annual average vertical velocity is then scaled to fit the sub-annual time span between the two LiDAR scans. Since glacier dynamics vary throughout a year this is done by minimising the RMSE with in-situ measurements.

The 500 MHz GPR survey was carried out from helicopter as done previously (Machguth et al., 2006). It covers 12.7 km of linear tracks with 12'000 radar traces. Travel times are converted to depth using a constant velocity estimation based on the measured snow density.

The corrected LiDAR-differentiation and the glaciological method show good agreement in the mean specific winter mass balance of 0.73 m w.e. and 0.78 m w.e. respectively. They disagree in crevassed areas and in the accumulation area where firn compaction affects the LiDAR-derived snow depth. The quality of the distributed mass balance that is used to obtain the correction for glacier flow directly limits the quality of the distributed snow depth data set. However, this data set allows analysing the relation of snow depth to surface topography such as elevation, slope and curvature. The performance of a multiple linear regression using these variables varies strongly within the glacierized area. So far, no simple model was found that could explain snow depth on the entire glacier with reasonable correlation.

Comparison with the GPR snow depth measurements indicates that the glaciological method is affected by a systematic bias that comes from non-representative sampling sites. Thereby, GPR proves to be an attractive tool for snow depth measurements with relatively small uncertainties. Unlike LiDAR-differentiation it is not affected by glacier dynamics and firn compaction in the accumulation area. However, LiDAR provides truly distributed data with high resolution that is not directly achieved by GPR or conventional glaciological measurements. The simultaneous availability of all three data sets is unique and their comparison and combination draws a detailed image of winter snow accumulation that benefits from each method's advantages.

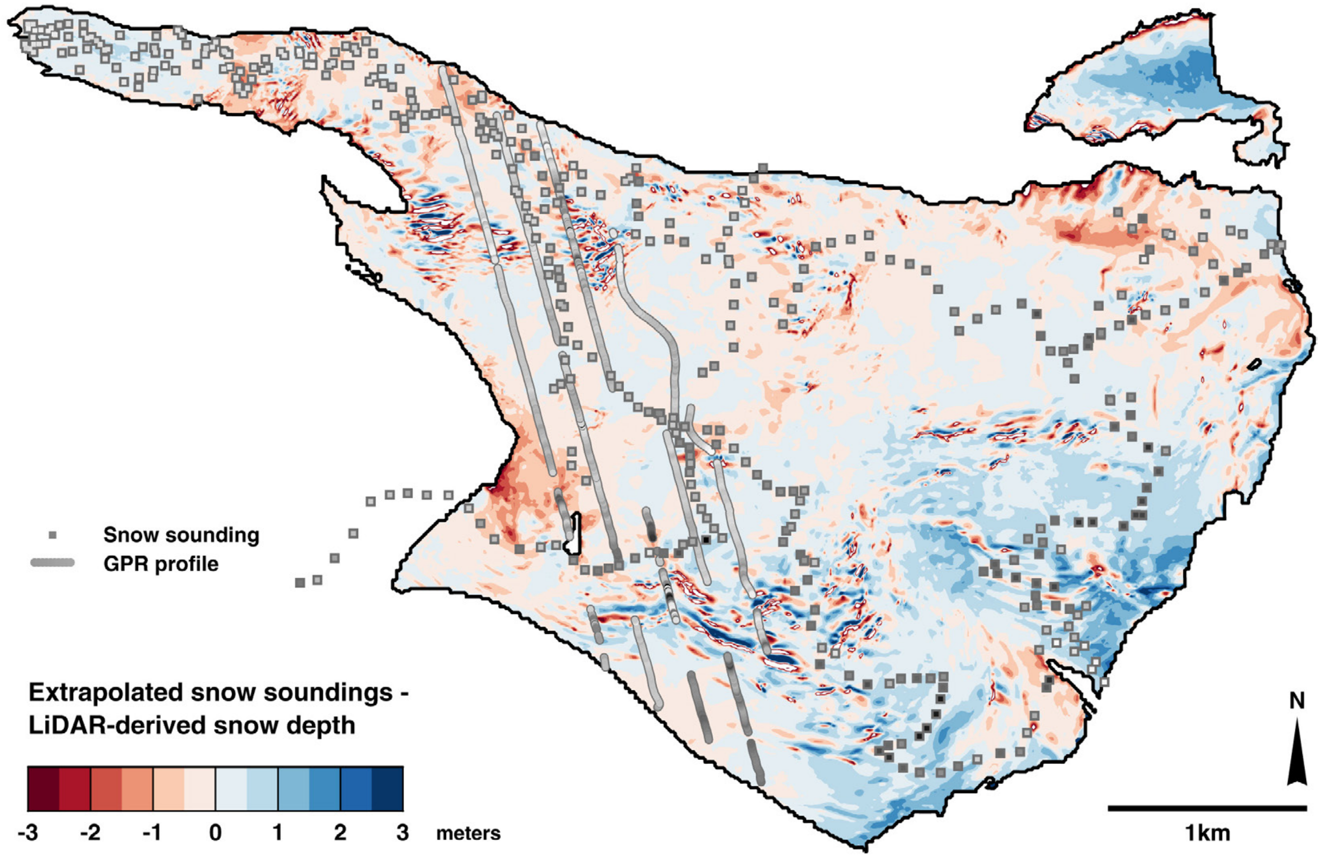

Figure 1. Snow probings, GPR profile lines and difference between corrected LiDAR-derived snow depth and extrapolated snow probings in April 2010 on Findelengletscher, Switzerland.

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11.10

Climate change impacts on glaciers and runoff in Tien Shan (Central Asia)

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Climate-driven changes in glacier-fed streamflow regimes have direct implications on freshwater supply, irrigation and hydropower potential. Reliable information about current and future glaciation and runoff is crucial for water allocation and, hence, for social and ecological stability. Although the impacts of climate change on glaciation and runoff have been addressed in previous work undertaken in the Tien Shan ('water tower of Central Asia'), a coherent, regional perspective of these findings has not been presented until now.

In our study, we explore the range of changes in glaciation in different climatic regions of the Tien Shan based on existing data. We show that the majority of Tien Shan glaciers experienced accelerated glacier wasting since the mid-1970s and that glacier shrinkage is most pronounced in peripheral, lower-elevation ranges near the densely populated forelands, where summers are dry and where snow and glacial meltwater is essential for water availability. The annual glacier area shrinkage rates since the mid-twentieth century are 0.38-0.76% a^{-1} in the outer ranges, 0.15-0.40% a^{-1} in the inner ranges and 0.05-0.31% a^{-1} in the eastern ranges. We used glacier change assessments based both on direct data (mass balance measurements) and on indirect data (aerial and satellite imagery, topographic maps). The latter can be plagued with high uncertainties and considerable errors, which highlights the need for continued *in-situ* mass balance and ice thickness measurements. Efforts should be encouraged to ensure the continuation and re-establishment of mass balance measurements on reference glaciers, as is currently the case at Karabatkak, Abramov and Golubin glaciers (Figure 1).

Although in the first instance shrinking glaciers supply ample quantities of water in the form of increased glacial runoff, reduced glacier volume will ultimately result in a decrease in both glacier-fed and total runoff, if there are no increases in water amount from other sources. Accordingly, long-term average annual runoff in Kyrgyzstan has increased from 47.1 km^3 (~1947–1972) to 50 km^3 (1973–2000) and the current level of total runoff is likely to remain stable in the near future or could even further increase slightly. By the end of the 21st century, however, total runoff is projected to be smaller than today. Analysis is still hampered by compensating effects such as changes in precipitation and evaporation as well as anthropogenic influences, rendering an appropriate identification of factors controlling discharge difficult. For instance, decreasing runoff during the ablation season can be compensated for by higher winter runoff from increased liquid precipitation. More integrative studies addressing changes in all runoff components (precipitation, groundwater, and meltwater from snow, glaciers and permafrost) are therefore required for better appraisal of the degree of glacial depletion and subsequent changes in glacial runoff. The impact of snowcover changes, black carbon and debris cover on glacier degradation needs to be studied in more detail. Only with such model approaches, reflecting transient changes in climate, snowcover, glaciation and runoff, can appropriate adaptation and mitigation strategies be developed within a realistic time horizon.

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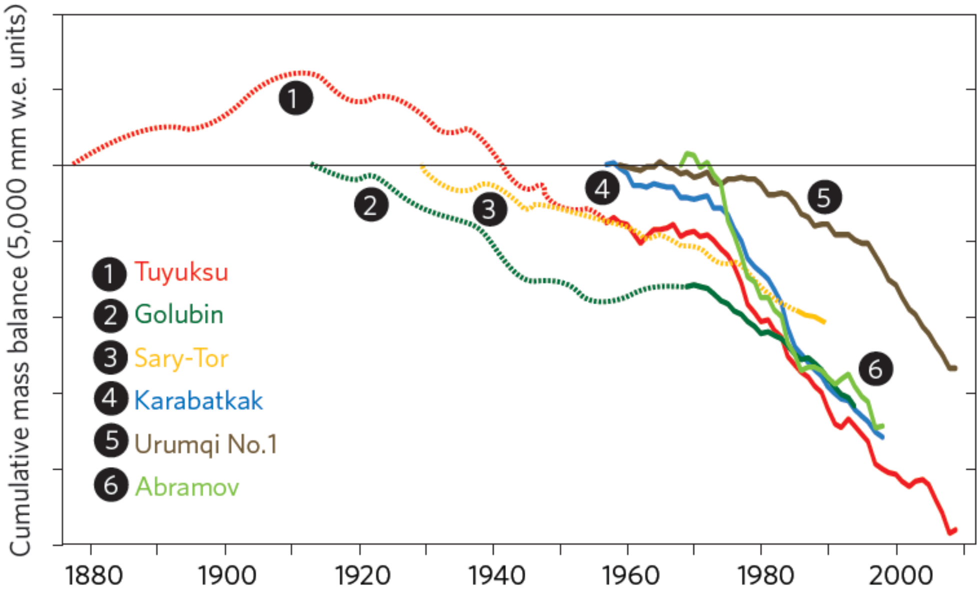

Figure 1. Cumulative mass balances (solid lines) and reconstructions (dashed lines) of selected Central Asian glaciers. The horizontal black line indicates the level at first measurement. Source: WGMS 2009 and earlier volumes.

P 11.1

Micro-computed tomography of salted snow

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High salt amounts (between 8-40 t salt per km) are applied during wintertime to maintain the safety of the national road network. A typical day of maintenance costs about 1mio Swiss Francs [1]. In addition, the melt water with high salt concentration is harmful for soil and groundwater [2, 3].

Although salt has been used for the treatment of snowy roads in wintertime for many years there is only limited understanding of the effect of salt to snow regarding thermodynamic and especially mechanical processes. The thermodynamics of salted snow, its sintering process and mechanical properties have not yet been systematically investigated or measured. Up to now there exist only little empirical data (e.g. [4]). Most of the theory on snow sintering and metamorphism is based on dry snow. Wet snow is mainly investigated for its hydraulic properties, but again little data exist for mechanical properties.

To understand the physical properties of salted snow information about microstructural properties is crucial. By micro-computed tomography (microCT), the three phases air, ice and brine (salt solution) can be distinguished due to their different X-ray absorption coefficients (Figure 1). All three phases can be observed in-situ. This opens the possibility to use time-lapse methods. Changes in size and distribution of air, brine and ice can be extracted afterwards.

Samples with increasing amount of NaCl-solution were mixed with snow and compressed under a load of ~2 bars for 2 h. Afterwards, the samples were analyzed by microCT. Results of the microCT evaluation will be shown.

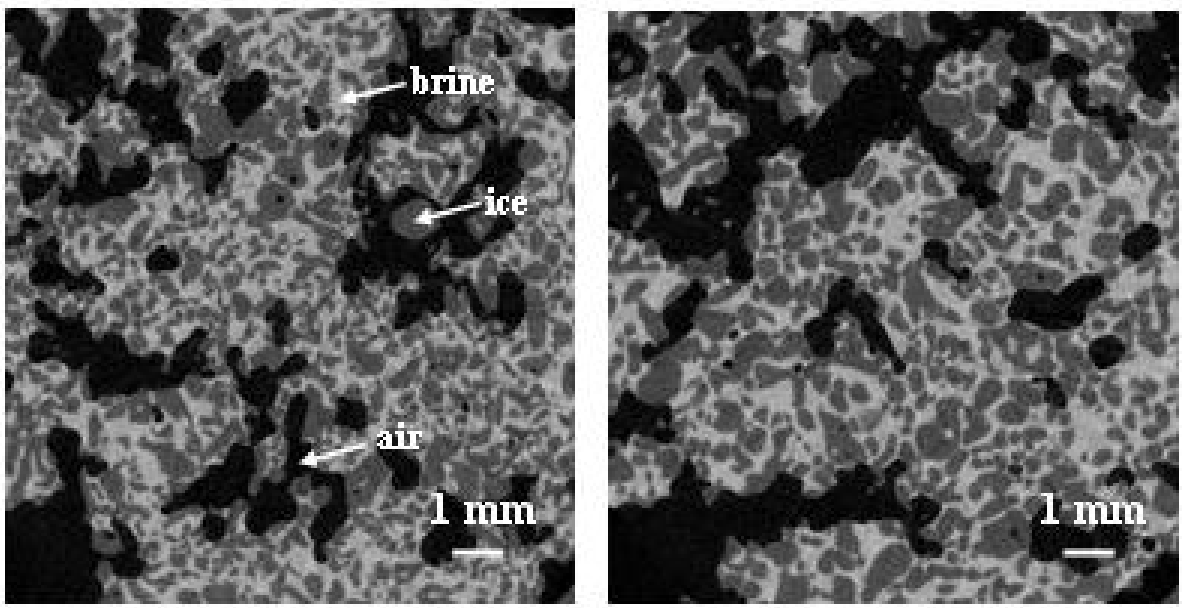

Figure 1) 2D micro-CT images of a salt-snow mixture with 45 w% NaCl measured at -18°C. *Left*: Sample immediately after adding and mixing with salt solution. *Right*: Same sample 21 days later.

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P 11.2

Orientation of snow crystals: Evolution of orientation during temperature gradient metamorphism

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The physical properties of snow are tied to its microstructure. Especially for the slow, plastic deformation of snow, the crystal orientation could be an important factor in addition to the geometry of the ice matrix. Micro-CT measures precisely the snow microstructure, but gives no information about the orientation of the ice crystals. In this study, we applied a temperature gradient of 40 K m^{-1} to two large blocks of undisturbed decomposed snow during 3 months. The absolute temperature at the sampling location was -20°C. Two closely spaced snow samples were taken before heating, then every week during the first month and afterwards every month. From each sampling period, one sample was analyzed in the micro-CT and the other was used for thin sections preparation. The thin sections were analyzed using a G50 fabric analyzer. The results show that not only the shape and size of the crystals change, but also the orientation. In our experiment, the orientation of the crystals change in one snow group from a predominantly vertically oriented c-axes fabric to a fabric where the c-axes are mainly horizontal, but randomly oriented in plane. In the other snow group, no evolution was observed. These preliminary results suggest that several factors impact the evolution of the crystal orientation, such as density, pore space and the initial snow crystal fabric.

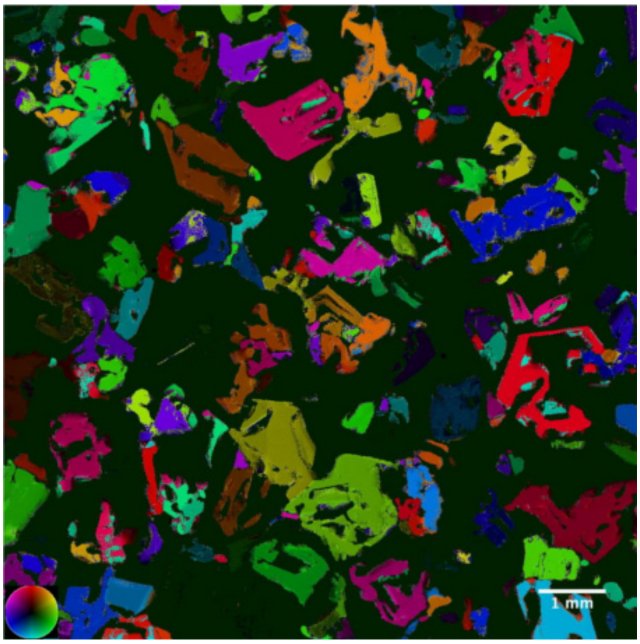

Figure 1. Depth hoar thin section analyzed with the Fabric analyzer G50. Each color corresponds to a different c-axis orientation of the snow crystals. C-axis orientation and color are related through a color wheel (bottom left).

P 11.3

Acoustic emissions related to avalanche release

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We intend to find acoustic precursors within the snowpack prior to avalanche release. The acoustic emission technique is commonly used to study the rupture of brittle materials (see, e.g. Johansen and Sornette, 2000). The rupture events are observed to obey power-law distributions (with exponent β). A change in the rupture process (transition from a stable to an unstable regime) can be associated with a change in the exponent β of the size-frequency distribution of the event energy and of the waiting time distribution of the events (Pisarenko and Sornette, 2003). Within natural hazards this behaviour was shown for icequakes prior to a glacier break-off by Faillettaz et al. (2011).

We performed laboratory experiments where we loaded snow samples containing a weak layer and measured acoustic emissions. Preliminary results suggest that prior to the catastrophic failure of the snow samples the change in exponent was observed as well.

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P 11.4

Tracer-LIF (Laser-Induced-Fluorescence) measurements of water flow through snow

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Many wet and gliding snow avalanches caused several accidents during the winter 2011/2012 in the European Alps, demonstrating the need for a better understanding of the formation of these events. Predicting regional wet snow avalanche danger depends on factors like the structure of the snowpack, the energy transferred from the atmosphere and the ground into the snowpack and the rate of water percolation through the snow. A lack of knowledge exists on the micro-scale water flow through snow. Most studies mainly quantify the total flow through the snow matrix for different snowpack layers neglecting the micro-scale flow dynamics and preferential flow path generation. A detailed description as a basis for quantitative understanding, however, requires investigations of the microscopic velocity fields in the pore space.

We present spatiotemporally highly resolved Tracer-LIF measurements of the water flow in the pore space of a wet snow sample driven by gravitational and capillary forces. For the experiments, cooled water seeded with fluorescent micron-sized particles (tracers) is carefully sprinkled onto the top of the snow sample, which is placed behind a Plexiglas window. The snow sample is illuminated with laser light and the fluorescent light of the tracers is filmed with a high-speed camera. The measurement resolution is 15 µm × 15 µm per pixel.

Fig. 1 shows the resulting, with tracer-LIF measured particle trajectories. Each velocity vector is labelled with a colour indicating the particle velocity at a specific location. The travel time of a relatively long particle track is included ($\Delta t = 0.84$ s). The total measurement time was 1.35 s. The path of this particle shows a strong deflection around a snow crystal of a size of about 1 mm. A wider flow path with a relatively high particle density and high particle velocities occurred around $\{x, z\} = \{5$ mm, 7 mm$\}$ in Fig. 1. Another interesting feature is found at $\{x, z\} = \{4$ mm, 2 mm$\}$. Particles enter a small pore space with a relatively high velocity, get deflected by the snow matrix performing almost a 360° loop at a lower velocity and leave the pore space again at a higher velocity. This flow loop and all other trajectories show that the flow within the snow sample is highly 3-dimensional.

LIF measurements were extensively used for investigations of the flow fields in porous media and fills, however, this is the first study applying LIF to snow. LIF measurements in snow will open a wide range of possible investigations like analysing capillary effects or the transition from water filled pores to melt water percolation.

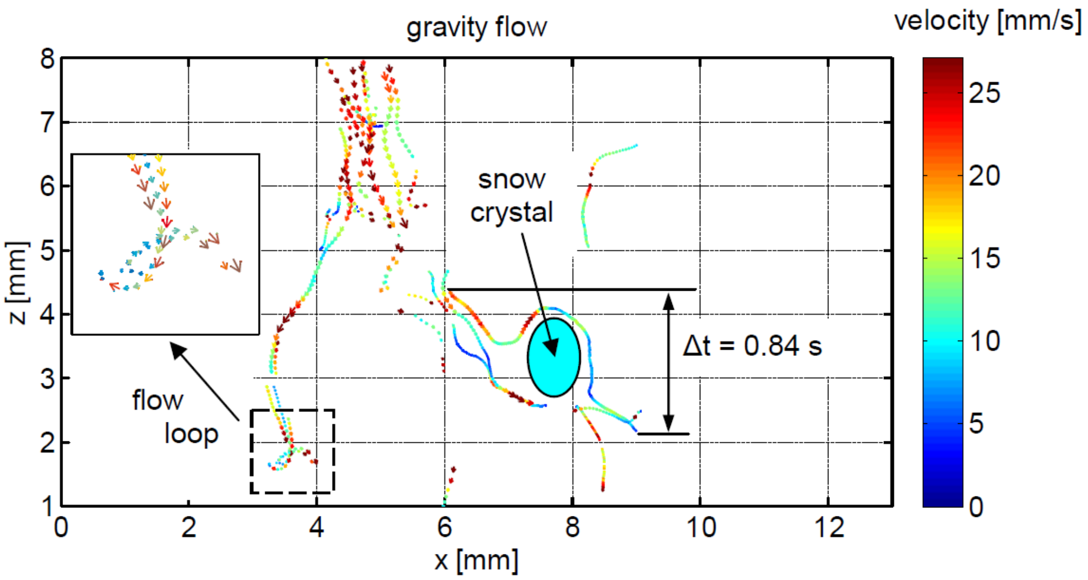

Figure 1. Particle trajectories for a gravity driven, saturated water flow in a wet snow sample. Colours of arrows indicate particle velocities.

P 11.5

Towards the automatic detection of seismic signals generated by snow avalanches

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Snow avalanche activity data represent the most direct instability data for avalanche forecasting. Avalanche activity is usually estimated based on visual observations, which are imprecise and impossible at night or when visibility is limited. To overcome this limitation, seismic monitoring has been developed over the last 20 years to detect snow avalanches. While it holds great potential, seismic detection of avalanches is not widely used due to a lack of accurate classification algorithms to detect avalanche events from passive seismic data. To tackle this problem, we used seismic data from a geophone directly inserted in an avalanche start zone. By visually analyzing the spectrogram of the seismic data, over 380 avalanches were identified for the winter of 2010 over an area of about 2 km2. To automatically detect these avalanche events in the seismic data, a pattern recognition workflow was developed. It consisted of three steps: 1) event selection, 2) feature extraction, and 3) classification. The results are quite promising: our workflow achieves 93% overall classification accuracy with 13% precision for detecting avalanches for the entire season. Though we obtained successful classification accuracies, the low precision rates of our model indicates that there is still room for improvement. In the coming winter, we therefore intend to deploy an array of geophones to allow for the localization and characterization of avalanches with the goal to improve the automatic avalanche detection workflow.

P 11.6

SNOWPACK model uncertainty and future trends of the Swiss snowpack

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Snow is a key feature of mountainous environments because of its high implications on hydrology, vegetation and economics, such as winter tourism or hydropower (Beniston et al. 2003, Marty 2008). In particular, snow depth, the stored snow water equivalent, the snow load on a roof or the duration of the snow on the ground are all important parameters for services like road maintenance, avalanche warning, water management, hydro power, flood prevention or building code regulations. The measurement of these snow parameters is either not always possible or too expensive. To overcome this problem, snow models are often used, such as the complex one-dimensional, physically based snow model SNOWPACK, which numerically solves the partial differential equations governing the mass, energy and momentum equation within the snowpack (Lehning et al. 2002).

In order to make meaningful statements considering the Alpine snow cover under future climatic conditions, it is very important to verify SNOWPACK in its ability to correctly model snow characteristics such as snow depth or duration of snow cover. As input data, SNOWPACK needs air temperature, relative humidity, wind speed and direction, incoming short- and long-wave radiation, and precipitation intensity. As most stations do not provide incoming long-wave radiation data, it needs to be parameterized, for example using methods described in Flerchinger et al. (2009). Moreover, due to wind-induced errors, it is not meaningful to take precipitation measurements directly as input into SNOWPACK, so they need to be calibrated or corrected.

The aim of this poster is to highlight the abilities of SNOWPACK in modeling various relevant snow parameters, as well as showing future trends of the Swiss snowpack at selected sites in Switzerland. Therefore we concentrate on the ability of SNOWPACK in modeling climatological characteristics of the snow cover, such as snow depth, maximum snow depth, length of snow season, and so on. For the assessment of the future trends, scenario data of the recently released CH2011 report will be used in order to perturb the observed time series of temperature and precipitation.

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P 11.7

Estimation of snow cover distribution in alpine catchments by application of airborne laser scanning

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The storage of winter precipitation in the snow cover is a substantial source for runoff generation in high mountain catchments. The spatial distribution of snow accumulation is influenced by topographic parameters, such as slope, aspect and wind exposure. In high alpine catchments complex relations exist between the glacier surface and the snow accumulation, and vice versa.

Measuring the snow cover distribution by in situ measurements in terms of snow probing and snow pits delivers spatially limited data due to the restricted accessibility in the rough terrain. Airborne laser scanning (ALS) is a remote sensing technique to record point information of the surface elevations with a high spatial density of several points per square meter. From these points digital elevation models (DEM) can be produced. Comparing the multi-temporal DEMs delivers surface elevation changes in a high spatial resolution of 1 meter and even higher.

Within the alpS project MUSICALS_A, ALS campaigns were conducted in the alpine catchments of the Ötztal Alps in autumn and spring. The surface elevation changes were initially interpreted in terms of snow depth and converted into snow water equivalent (SWE) using a statistical relation between observed snow densities and snow depths. These maps of SWE show characteristically snow accumulation patterns due to glaciation and redistribution processes forced by wind and gravity and thus provide an ideal basis for comparison with model outputs of fully distributed snow hydrological models (e.g. AMUNDSEN). Results can be used for calibration of the model components in terms of total precipitation sums and snow redistribution. Hence runoff generated by spatial differentiated snow melt can be modelled more realistically.

On glacier surfaces dynamical processes of ice flow and compaction of firn additionally induce surface elevation changes at these areas, both with negative and positive signs. A set of in-situ measurements of snow depth by ground penetrating radar, DGPS measurements and snow probing at glacier surface was compared to elevation changes measured by application of ALS for one snow accumulation season. The magnitude of elevation changes caused by snow and ice dynamical processes can be detected by the combination of these methods.

P 11.8

Historical glacier variations in southern South America since the Little Ice Age: examples from Lago Viedma (southern Patagonia) and Mendoza (central Andes)

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There is considerable historical evidence for European glacier dynamics over the past centuries. Evaluation of this information allows reconstructing glacier length variations from the Little Ice Age (LIA) until the present. For several glaciers, reconstructions with decadal or annual resolution can be achieved (e.g. Zumbühl *et al.* 2008, Nussbaumer and Zumbühl, 2012). These revealed that there is a striking asynchrony between Alpine and Scandinavian glacier fluctuations, both during the LIA and in the 20th century. In South America, historical information is much less abundant, but early photographs and maps depict changes for selected glaciers before the onset of modern measurements.

Here we provide new evidence to the South American glacier history. Written documents and pictorial historical records (drawings, sketches, engravings, photographs, chronicles, topographic maps) have been critically analysed, with a particular focus on two regions: Lago Viedma (El Chaltén, southern Patagonia, 49.5°S, 73.0°W) and the Río del Plomo basin (Mendoza, central Andes, 33.1°S, 69.9°W).

For the Lago Viedma area, early historical data for the end of the 19th century stem from the expedition of the Chilean-Argentinean border commission (led by the Argentine Francisco P. Moreno). Glaciar Viedma, an outlet glacier of the Southern Patagonian Icefield, is richly documented. In addition, the expedition by the German Scientific Society, conducted between 1910 and 1916, and the photographs by Alberto M. de Agostini, an Italian padre, geographer and ethnographer, give an excellent depiction of the glaciers.

For the Mendoza area, historical sources go back to the arrival of the Spanish conquerors, particularly related to the finding of new routes across the high Andes in the second half of the 18th century. In the beginning of the 20th century, Robert Helbling (1874–1954), a Swiss geologist and pioneer of alpinism, explored the Argentinean-Chilean Andes together with his friend Friedrich Reichert (Reichert, 1946). In the summer of 1909/10, they started a detailed survey of the highly glacierized Juncal-Tupungato mountains, leading in 1914 to the first accurate topographic map of the area. In 1934, the sudden drainage of a glacier-dammed lake in the upper Río del Plomo valley caused fatalities and considerable damage to constructions and the Transandine Railway. A similar event is reported to have occurred in 1786 according to historical records.

Finally we compare the observed glacier fluctuations of the two regions with other glacier reconstructions available (e.g. for northern Patagonia), to give an overview of the glacier evolution in southern South America since the LIA. According to historical evidence and dendro-geomorphological analyses, the LIA maximum occurred between the 16th and 18th century. However, there is a large spatial variability (Masiokas *et al.* 2009). Those observations can be compared with recently developed, high-resolution multi-proxy temperature and precipitation reconstructions. This allows an assessment of the spatial pattern of glacier changes in southern South America, differentiating local effects from regional or larger-scale climate dynamics.

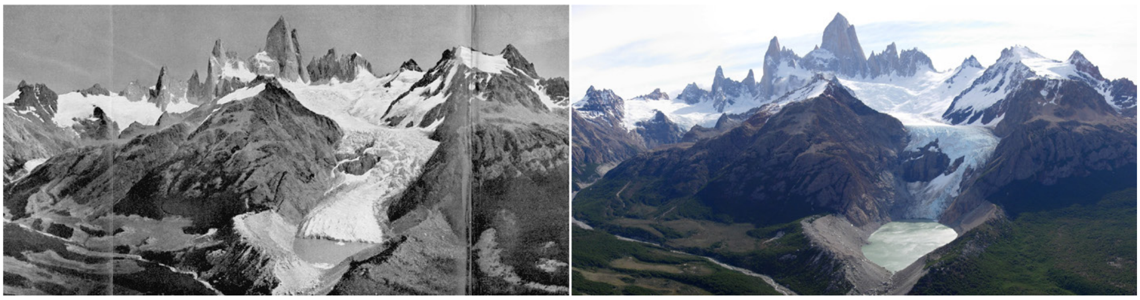

Figure 1. Comparison of Glaciar Piedras Blancas (El Chaltén, southern Patagonia) in 1931 (photo by A. M. de Agostini) and 2012 (photo by S. Nussbaumer).

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P 11.9

Current evolution of some high mountain debris-covered glaciers in western Alps

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The Alps and the cryosphere are some of geographical regions and geosystems the most affected by the current global change. However, local alpine environmental responses are heterogeneous and complex. In this way, numerous glacier system behaviours exist, depending of various regional (*e.g.* annual temperature and precipitation) and local (*e.g.* solar radiation, distribution and thickness of debris cover) factors. Valley ice-bared glaciers are broadly more sensitive to climate variations than high mountain debris-covered glaciers. Indeed, the occurrence of debris mantle (insulation layer) and the localization of this kind of glacier systems within the periglacial belt (roughly above the isogeotherm of -2°C) allow a better preservation of the ice.

Differential GPS measurements and Electrical Resistivity Tomography surveys were carried out on Les Rognes - Pierre Ronde (Mont-Blanc Massif, France), Entre la Reille (Diablerets Massif, Vaud) and Tsarmine (Pennic Alps, Valais) glacier systems. Due to their topographical situation and the numerous Holocene climatic variations, they are characterized by large amounts of debris in the distal part (morainic dam). Periglacial landforms (rock glaciers, push-moraines) occur in these systems located within the periglacial belt. Moreover, the negative mass balance of these glacier systems is reflected by the absence (or limited existence) of an accumulation area (and so the limitation of ice supply) and by the covering of the ablation area on which ice volume is slowly decreasing. In this poster we discuss the kinematics and the internal structure of these three glacier systems.

P 11.10

Ice volumes in the Himalayas and Karakoram: evaluating different assessment methods

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Knowledge about the mass of freshwater stored in Himalayan and Karakoram (HK) glaciers is of particular interest, as this region has the largest glacier coverage outside the polar regions, and hundreds of millions of people live in the lowlands along the rivers draining these mountains. Recent debates, including the so-called 'IPCC glaciergate', revealed considerable gaps of knowledge and understanding of glaciers in this region (e.g. Bolch et al. 2012). Better information about glacier volumes and the ice thickness distribution are required to improve assessments of the future development of these glaciers and their impacts on the hydrological cycle. As direct measurements of glacier volumes on regional scales are not possible, ice thickness and volume assessments have strongly to rely on modeling approaches. Here, we estimate ice volumes of all glaciers in HK using three different approaches, compare the results, and examine related uncertainties and variability.

The approaches used included volume-area scaling using different scaling parameters, a slope-dependent thickness estimation (adapted from Haeberli & Hoelzle 1995), and a new approach to model the ice-thickness distribution based on the approach of Linsbauer et al. (2012). Glacier outlines have been compiled from different state-of-the-art glacier inventories (Bajracharya and Shrestha 2011; Frey et al. 2012) and revealed an overall ice covered area of ~40,800 km² (Bolch et al. 2012). Topographic information has been obtained from the void-filled version of the Shuttle Radar Topography Mission digital elevation model (SRTM DEM).

The volume-area scaling approach resulted in glacier volumes ranging from 3632 to 6455 km^3, depending on the scaling parameters used. The approach for slope-dependent thickness estimations had to be adjusted to the modern glacier inventory data, and generated a total ice volume of 2330 km^3. A total volume of 2955 km^3 resulted from the modified ice-thickness distribution model. With the exception of the volume-area scaling, results are clearly at the lower bound of previous estimates or even smaller, and possibly hint at an overestimation of the potential contribution of HK glaciers to sea-level rise.
The range of results also indicates that large uncertainties still persist in ice volume estimations. Comparisons with *in situ* measurements like ground penetrating radar (GPR) are hampered by the fact that (a) almost no suitable results of GPR measurements on glaciers are available for the study region; and (b) that only the results of the ice-thickness distribution model would allow such comparisons. By applying different combinations of model parameters and by altering glacier areas by ±5%, uncertainties related to the different methods are evaluated.

The distributed ice-thickness modeling approach leads to the most reliable results, as it is based on simple but robust ice-mechanical considerations rather than extrapolated statistical relations. It allows comparisons with *in situ* measurements and it has numerous potential further applications (Linsbauer et al. 2012). Therefore, the use of such models can be recommended, although they are more labor intensive than statistical scaling approaches. In combination with digital glacier outlines and DEMs with (near-) global coverage, they offer the possibility to improve ice-volume estimations of the HK region, but also of other glacierized mountain ranges.

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P 11.11

Information on glacier dynamics from probabilistic icequakes location (Triftgletscher, Switzerland)

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The precise characterization of icequake sources offers valuable insights into local stress, the presence of water and basal sliding. The reliability of the conclusions however strongly depends on the accuracy of hypocentral locations, which is therefore a key point for the interpretation of icequakes record in terms of glaciological processes. The present study focuses on seismic data from Triftglescher, Switzerland, which has been monitored since 2007 due to its steep tongue prone to break-off. Using continuous seismic records from an on ice campaign network we determine icequake hypocenters with the probabilistic source location method implemented in the software NonLinLoc. The calculations offer a perspective on what degree of accuracy can be achieved for icequake locations. Investigated area was described by means of a 3D velocity model including both ice and bedrock media. Our locations reveal icequake sources near the glacier surface as well as near the bed.

We interpret both types of events in terms of glacier dynamics: shallow seismic emission is discussed with the help of surface strain rate analysis, and the capability of near bedrock icequakes to be explained with double couple source mechanisms or tensile fracturing is assessed. Finally, we propose some clues for the detection of periods characterized by enhanced break-off risk.

P 11.12

Using glacio-speleological methods to test GPR interpretations about changes in dynamics, thermal state and drainage system of Tellbreen, a high arctic glacier on Svalbard

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Glacier response to climate change has attracted a large amount of research effort in recent years (WGMS, 2008). Most of this has focused on glacier changes in length, area, volume and mass. However, glaciers can also respond to climate change by altering their thermal condition and drainage system configuration. In turn, these internal changes can influence glacier dynamics and mass balance, and either damp or amplify glacier response to climatic forcings. Relatively little research has been conducted on long-term internal changes to glacier systems, largely due to the difficulty of obtaining data on past glacier states.

Recent developments in glacio-speleology have opened up new opportunities to make direct observations of glacier drainage systems, and gain access to glacier beds and basal ice sequences (Gulley et al., 2009a, b). Exploration of englacial and subglacial conduits, therefore, allows the simultaneous investigation of: (1) the present state of the glacier drainage system and basal thermal regime; and (2) past states of the glacier through study of basal ice characteristics.

In 2011 and 2012 speleological mapping of 3 different caves has been conducted in Tellbreen, a cold-based glacier in central Spitsbergen, Norway. These explorations have shown that the conduits have both englacial and subglacial components, and some sections are even incised into the glacial till. Furthermore, these findings indicate that Tellbreen had formerly at least partly a temperate bed and was much more dynamically and geomorphologically active during its Little Ice Age maxima than it is today.

This study demonstrates the capability and applicability of glacio-speleology to test findings based on indirect methods such as Ground Penetrating Radar (GPR) made by Baelum & Benn (2011). Additionally it reveals the present and especially the past behaviour of Tellbreen in a new light.

Figure 1. Exploring and mapping of one side channel of Smokey Cave in Tellbreen. Channel dimensions at this position: width 9m and height 3m. © Philipp Schuppli

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P 11.13

Understanding the response of very small glaciers in the Swiss Alps to climate change: An integrated study approach applying different monitoring techniques

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To date, glaciological research in the European Alps (especially in the Swiss Alps) has been focussing on medium and large valley glaciers (> 3 km^2), which account for the major part of the glazierized area and ice volume or fresh water storage. However, present knowledge about Alpine glaciers is somehow not representative in terms of glacier size distribution, as more than 80% of all Swiss glaciers are smaller than 0.5 km^2 (Huss 2010). They belong to the class of very small glaciers, occurring mostly in cirques, niches and below headwalls where topoclimatical factors and snow accumulation patterns are favourable for the persistence of snow and ice. It is not clear whether the findings and theoretical concepts elaborated for medium and large valley glaciers can be transferred one to one to very small glaciers (Kuhn 1995). Thus, this study takes a first step in filling the relevant knowledge gap about the behaviour and response of very small glaciers in the Swiss Alps to climate change.

So far, the only very small glacier investigated in Switzerland is Pizol glacier (SG), where direct mass balance measurements since 2006 provide a first example for their response to climate change (Huss 2010). This mass balance monitoring program will be continued as part of this study. Furthermore, a number of additional very small glaciers covering the entire Swiss Alps was chosen as appropriate study glaciers. This year, direct mass balance measurement campaigns have been started on Glacier du Sex Rouge (VD), St. Annafirn and Schwarzbachfirn (UR), Blauschnee (AI) and Vadret da Corvatsch (GR). Planned annual terrestrial LiDAR surveys of the surface of these glaciers will allow derivation of geodetic mass balances as well.
Measured ice thickness data is available for some few very small glaciers. This database is being extended within this study. Ice thickness was already directly measured on St. Annafirn (UR) and Glacier du Sex Rouge (VD) using Ground Penetrating Radar (GPR). Further GPR surveys on other glaciers will follow.

The first results gained so far show that topoclimatical factors, snow redistribution (wind drift) and avalanching seem indeed to play an important role in the mass balance of very small glaciers. Accumulation and ablation patterns show a high small-scale variability. Over the past few decades, very small glaciers in the Swiss Alps vanished dramatically and even more than large or medium sized valley glaciers. Thus, they probably react more sensitive and faster to current climate change. From 2006 to 2011, Pizol glacier showed large mean annual mass losses of about 1.5 m w.e. Surface area and ice volume losses are significant as well. Since 1850, St. Annafirn (UR) lost more than 80% of its surface area, with an accelerating trend over the past four decades. On average, St. Annafirn is still about 13 m thick, with maximum thicknesses up to 40 m (Fig. 1). The estimated ice volume is 2'197'000 m^3 (0.0022 km^3). This corresponds to one third of its modeled ice volume in 1973 (Linsbauer et al. 2012). The freshwater still stored in St. Annafirn roughly amounts to 2/3 of the volume of Lake St. Moritz.

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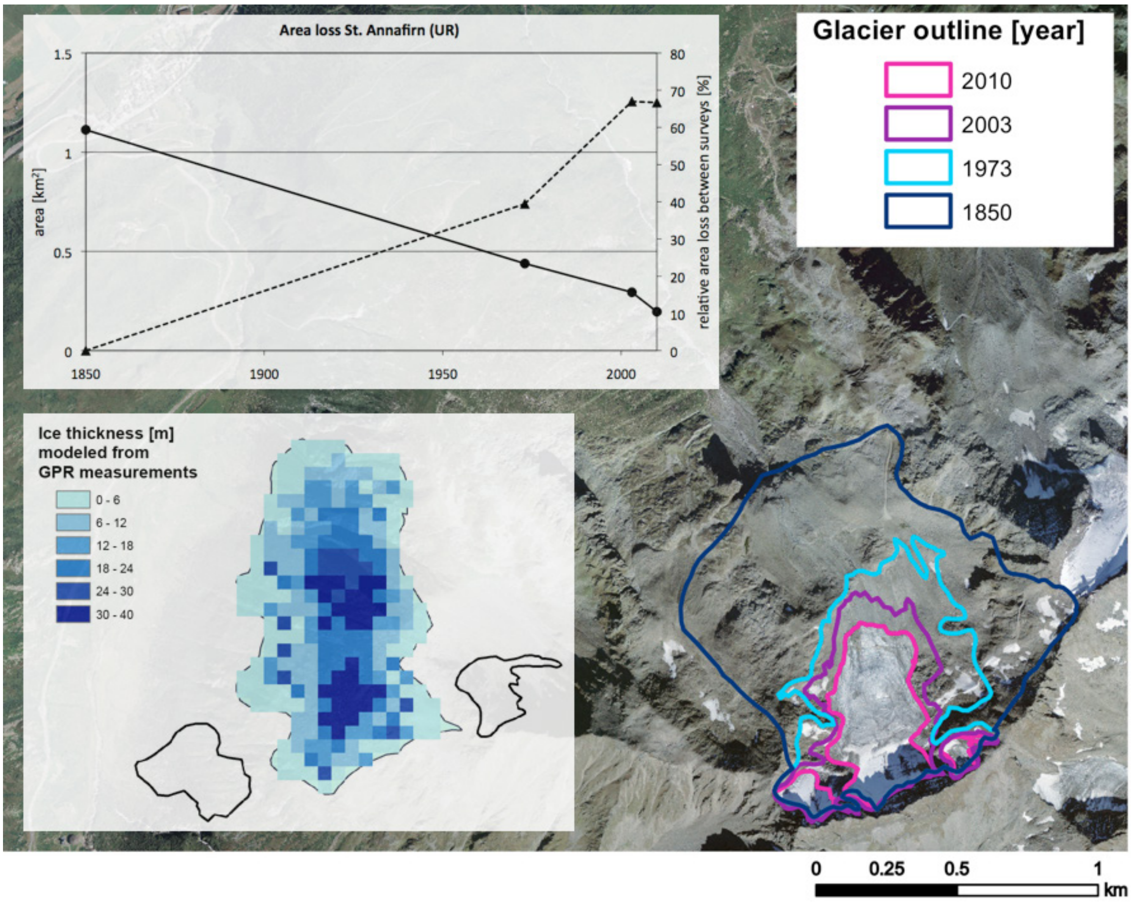

Figure 1. St. Annafirn near Gemsstock (Andermatt, UR): Area loss since 1850 and current (2012) ice thickness modeled from linear GPR measurements. Underlain to the digitized glacier outlines is a high-resolution (25 cm) swissimage orthophoto taken in autumn 2010 (swisstopo).

P 11.14

A straightforward method for the automated calculation of glacier flow lines.

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Glacier flow lines are an important concept in glaciology. Basically they describe the direction of the ice flow from accumulation zone to the ablation area. Flow lines are used in various flow modelling concepts (e.g. Greuell, 1992) and they are essential to assess the length of a glacier.

Nevertheless, defining glacier flow lines on complex glacier geometries is not a trivial task and certain properties of the glacier surface (e.g. convex cross-sectional surfaces in the ablation areas) prevent the calculation of flow lines from using hydrological flow models. Flow lines are generally drawn manually, an approach that becomes unfeasible when flow lines for large glacier samples would be required. Only recently a first semi-automatic method has been developed that allows calculating central flow lines using GIS software (Le Bris, subm).

Here a straightforward approach for the calculation of surface glacier flow direction is presented. For input the flow line computation requires glacier polygons and a Digital Elevation Model (DEM). The method relies on two basic criteria and a series of trade-off functions between them. The output is a set of flow lines comprising every individual branch of a glacier. The approach is fully automated and no glacier, glacier-type or region specific adjustments are made.

The method was tested for regions with numerous local glaciers on Greenland (i.e. outside of the ice sheet). Thereby the flow line computation was found to work well on all types of glaciers including the ice caps. The DEM used is of intermediate quality (GIMP-DEM, Howat et al., in preparation) and it remains to be tested to what degree a lower quality DEM (e.g. GDEM v2, Tachikawa et al., 2011) will influence model performance.

The automated computation of flow lines for extensive glacier samples is believed to open up new possibilities in glacier flow modelling and calculation of past as well as future glacier extent. At the same time a more automated determination of geometrical properties such as the glacier length might become possible.

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P 11.15

Caterpillar-like flow of the Greenland Ice Sheet: observations of basal control on ice motion.

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Caterpillar-like flow of the Greenland Ice Sheet: observations of basal control on ice motion. Varying basal motion due to episodic basal water supply is a long-established component of ice flow. However, the physical processes that govern the role of water in basal motion still remain only weakly understood. We instrumented four boreholes at two sites with sensor systems to better understand the processes controlling seasonal flow velocity variations in the marginal zone of the Greenland Ice Sheet. We present measurements of borehole deformation, subglacial water pressure and surface motion during one year (July 2011 to September 2012). Subglacial water pressure and ice deformation show periodic variations on several time scales which are delayed by up to half a period, depending on sensor depth. These observations are interpreted as ice motion in a caterpillar-like fashion, as opposed to the conventionally assumed shear flow. Using a time-dependent, Full-Stokes ice flow model we find that spatially and temporally varying basal motion can explain the observed variations in deformation, and the delayed reaction at different depths. These new data show that the reaction to basal motion is not uniform throughout the ice column, but varies with depth.

P 11.16

Complex age-depth relation in a mid-latitude glacier

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Glacier highstands since the Last Glacial Maximum are well documented for many regions, but little is known about glacier fluctuations and lowstands during the Holocene. This is due to the fact that the minimum extent is not imprinted in specific features like terminal moraines and that those areas are currently ice covered, limiting the access to sample material. In this study we report a different approach, using a 72 meter long surface-to-bedrock ice core drilled on Tsambagarav glacier in the Mongolian Altai (4140 m asl, 48°39.338'N, 90°50.826'E). This for the region typical flat-top glacier has low ice temperatures and a flat bedrock topography at the drill site which are ideal properties for a climate archive.

The ice core from Tsambagarav glacier was dated with a variety of methods, including identification of reference horizons, annual layer counting, nuclear dating with ^{210}Pb, and a novel ^{14}C technique.
The upper two third of the ice core correspond to the period 1815 to 2009 AD with annual resolution and strictly follows simple glacier flow models proposed by Nye (1963) or Thompson et al., (1990). For the lower third of the ice core faster layer thinning than predicted by flow models was identified. Such characteristic has already been noticed before for other midlatitude glaciers frozen to bedrock (Thompson et al., 1998). The section 43 to 52 m weq experiences stronger thinning than the section below and above, a characteristic we explain through varying accumulation rates. To deduce a continuous timescale an empirical equation was derived by using the ^{14}C results.

Radiocarbon measurements of the basal ice revealed an age of approximately 6000 years before present (BP). We interpret the basal ice age as indicative of ice-free conditions at 4100 m asl prior to 6000 years BP. This age marks the onset of the Neoglaciation at the end of the Holocene Climate Optimum. Since most glaciers in the Mongolian Altai have comparable or lower elevation we conclude that they are not remnants of the Last Glacial Maximum but were formed during the second part of the Holocene. The ice core derived accumulation suggests significant changes in the precipitation pattern over the last 6000 years. During formation of the glacier wetter conditions than presently prevailed, followed by a long dry period from 5000 years BP until 250 years ago. This is consistent with the precipitation evolution from lake sediment studies in the Altai.

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P 11.17

Ice level changes from seasonal to decadal time-scale at Lava Beds National Monument, NE California, USA

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Numerous lava tube caves host seasonal or perennial ice accumulation in the Lava Beds region (Halliday 1954, Knox & Gale 1959). Regular ice level monitoring has been conducted for eight ice caves since 1990, and additional five caves were also included into the monitoring network during recent years.
Monitoring data reveal that the seasonal cave ice phenology can be characterized by autumnal ice level low-stands. Regarding the multiannual evolution, both positive and negative ice mass balance periods were detected during the past 23 years.
Positive mass balances were reported for many caves from the late 1990s. Ice level is still stable in Skull Ice Cave, B-020 and U-200. However severe ice loss has characterized the evolution of the other caves. Major ice loss started in 1998-99 in the Merrill, C-270 and M-470 ice caves, while not until 2003 in L-800.
The recent rapid ice melt was fatal for some caves. Perennial ice disappeared from M-470 and M-475 by 2005 and from Merrill Ice Cave by 2006, for instance.

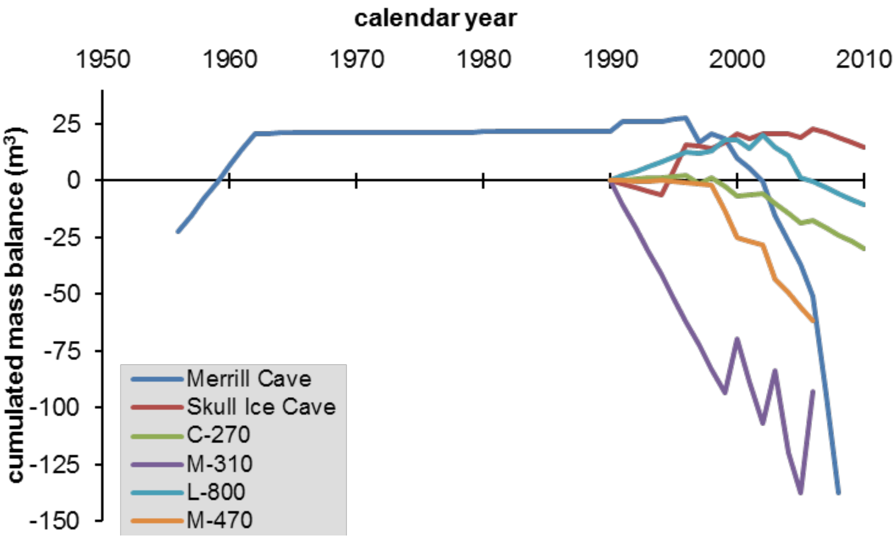

Figure 1. Secular decline of ice volume in six major Lava Beds NM perennial cave ice deposits.
Historical ice level changes can be extended back to 1956 at Merrill Ice Cave by ice level estimations based on stratigraphic (Sowers & Devereaux 2000) and archival photographic (Fuhrmann 2007) records.

Acknowledgment: Thanks to the National Park Service (NPS) and Lava Beds National Monument for making ice monitoring data available through an NPS Research Permit. Thanks to ISO-TREE (Sciex code:10.255.) and "Lendület" program of the Hungarian Academy of Sciences for support. ZK expresses thanks to Markus Leuenberger to host at the University of Bern.

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P 11.18

Towards an integrative analysis of mountain permafrost monitoring elements

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Surface and subsurface characteristics have to be considered in addition to climatic variables to evaluate the sensitivity of mountain permafrost to changing atmospheric conditions. To this end, the sub-project TEMPS-B of the newly funded SNF Sinergia project «The Evolution of Mountain Permafrost in Switzerland» (TEMPS, 2011–2014) follows a landform-specific approach. It utilizes a vast data set available from two decades of permafrost monitoring in Switzerland, which comprises meteorological, geophysical, kinematic, and ground thermal parameters from more than 20 established sites in the Swiss Alps.

It was shown in a few case studies that the different monitoring parameters complement each. Their joint analysis is essential in order to comprehensively understand the response of mountain permafrost to climatic changes. In the TEMPS-B project, the unique data set from the PERMOS network is used together with the data from a new automatic geoelectric monitoring system and a model to calculate ice and water contents for a time-dependent quantification of the subsurface composition of various sites featuring different typical permafrost landforms. By this, the interdependencies between atmospheric forcing and changes in subsurface ice and water contents as well as ground temperatures are analyzed on a broader scale. This will enable sound statements beyond singular case studies.

To perform joint statistical analyses of the different monitoring parameters, the data will be integrated and homogenized in the first place. In a next step, e.g. landform-specific dominant factors responsible for changes in subsurface ice and water contents or regional climatic impacts on different permafrost sites can be identified. Further, the 4-phase fractional composition (rock/air/ice/water) of the subsurface and its temporal changes shall systematically be determined for different landforms based on individual geophysical surveys and high-resolution geophysical monitoring.

P 11.19

The evolution of ground surface temperatures and rock glacier dynamics in the Furggentälti Valley (Gemmi, VS)

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In the western part of the Swiss Alps near the Gemmipass, a long-term permafrost monitoring site has been installed by the University of Berne in 1987 to observe the further development of three rock glaciers and different periglacial processes and landforms (Mihajlovic et al. 2003). Situated in a relatively warm and wet climate at elevation levels between 2450 and 2850 m asl., this test area became one of the longest permafrost-related temperature and kinematics time series in the Swiss Alps and owns the "reference site" status within the national permafrost monitoring network PERMOS. The main goal of the current research in this area is to improve the understanding of the rock glacier dynamics regarding the evolution of ground surface temperatures and terrain movements observed during the past two decades.

Over the monitoring period several climatic events occurred and the air and ground temperatures and the kinematics as well show significant changes in long-term and a high seasonal and interannual variability. Furthermore the activity pattern and the morphology of the largest and lowermost rock glacier in the valley were completely changing during the last decade. Some parts at the rock glacier sides seem to become inactive while creep velocities in the center were increasing up to 400% compared to the average velocity before 1990 and thus forming distinctive shear zones (Krummenacher et al. 2008).

A signal-response analysis using meteorological data, ground surface temperatures, terrestrial photographs and kinematic data show that the overall rock glacier movements react very sensitive to climatic events (e.g. Delaloye et al. 2008 and Kääb et al. 2007). As the snow cover is modulating the atmospheric forcing at the ground surface and thus represents a key parameter for the ground thermal regime, its dynamics might also have a big influence on the kinematics. Probably a mostly temperature-driven creep mechanism is superimposed by landslide-like movement components which are sensitive to melt water infiltration and therefore causing acceleration connected to the snow melt period (like discussed in Ikeda et al. 2008). Compared with findings from other permafrost research sites in the Swiss Alps, the interannual variability of rock glacier creep follows a similar pattern (Delaloye et al. 2008).

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