9. Open Cryosphere Session
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*Swiss Snow, Ice and Permafrost Society*

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9.1

Study of the retreat of a lake-calving glacier terminus, Triftgletscher (Switzerland).

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From 2000 to 2006, Triftgletscher (Bernese Alps, Switzerland) has retreated substantially and a proglacial lake containing $5 \times 10^6$ m$^3$ water has progressively formed in the glacier forefield. One of the consequences of the tongue retreat is the destabilization of the steep part behind it, likely to result in the release of ice avalanches with several million m$^3$ of ice plunging into the lake. Moreover, studies on the avalanches dynamics and lake hydraulics have shown that such avalanches could generate dangerous flood waves, thus posing a threat to the inhabitants of Gadmertal. In this context, the modelling of the terminus retreat appears relevant regarding the information it provides about how fast the lake forms and consequently about the steep part destabilization.

An important question regarding glaciers ending in lakes is to what extent the water contact influences their advances or retreat. Indeed, it is well known that iceberg calving can be a very efficient ablation mechanism. We propose to assess the role played by calving in the Triftgletscher tongue retreat using a simple mass balance model coupled with a calving model. The mass balance model is a temperature-index melt and accumulation model based on a linear relation between mete rate and positive air temperature. The calving criterion we use implies that as soon as the elevation of a surface point behind the calving front becomes equal to the flotation level, the portion between the point and the glacier terminus is removed.

Results show that the calving effect allows to explain 89% of the observed tongue retreat, whereas surface melting alone only accounts for 59%. They also indicate that the total ice mass in the lake area would have disappeared two years later in the absence of calving. We point out some limitations of the modelling concerning its application at a yearly time scale. In this case, it appears that potential floating sustainments are likely to induce substantial delays in the calving at the front, affecting thus the model results relevance.

9.2

Prediction of alpine glacier sliding instabilities: a new hope

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Mechanical and sliding instabilities are the two processes which may lead to breaking off events of large ice masses. Mechanical instabilities mainly affect unbalanced cold hanging glaciers (i.e. the snow accumulation isonly partly compensated by break-off at the front). For the latter case a prediction of such an event could be achieved based on data of surface velocities and seismic activity (Faillettaz et al., 2011a). The case of sliding instability is more problematic. Sliding instabilities occur on temperate glacier tongues. Such instabilities are strongly affected by the subglacial hydrology: infiltrated melt water may cause (i) a lubrication of the bed and (ii) a decrease of the effective pressure at the glacier bed and consequently a decrease of basal friction. Available data from Allalingletscher (Valais) indicate that the glacier tongue experienced an active phase during 2-3 weeks in summer or fall in most years with strongly enhanced surface velocities.

In order to scrutinize in more detail the processes governing the sliding instabilities, a numerical model developed to investigate gravitational instabilities in heterogeneous media (Faillettaz et al., 2010, Faillettaz et al. 2011b) was applied to Allalingletscher. This model enables to account for various geometric configurations, interaction between sliding and tension cracking and water flow at the bedrock.
We could show that both a critical geometrical configuration of the glacier tongue and the existence of a distributed drainage network were the main causes of this catastrophic break-off. Moreover, this model casts a gleam of hope for a better understanding of the ultimate rupture of such glacier sliding instabilities.

REFERENCES

9.3
Derivation and analysis of a high-resolution estimate of global permafrost zonation

Stephan Gruber

Permafrost underlies much of Earth’s surface and interacts with climate, eco-systems and human systems. It is a complex phenomenon controlled by climate and (sub-) surface properties and reacts to change with variable delay. Heterogeneity and sparse data challenge the modeling of its spatial distribution. Currently, there is no data set to adequately inform global studies of permafrost. The available data set for the Northern hemisphere is frequently used for model evaluation, but its quality and consistency are difficult to assess.

A global model of permafrost extent and dataset of permafrost zonation are presented and discussed, extending earlier studies by including the Southern hemisphere, by consistent data and methods, and most importantly, by attention to uncertainty and scaling. Established relationships between air temperature and the occurrence of permafrost are reformulated into a model that is parametrized using published estimates. It is run with a high-resolution (< 1km) global elevation data and air temperatures based on the NCAR-NCEP reanalysis and CRU TS 2.0. The resulting data provides more spatial detail and a consistent extrapolation to remote regions, while aggregated values resemble previous studies. The estimated uncertainties affect regional patterns and aggregate number, but provide interesting insight.

The permafrost area, i.e. the actual surface area underlain by permafrost, north of 60°S is estimated to be 13–18 million km² or 9–14% of the exposed land surface. The global permafrost area including Antarctic and sub-sea permafrost is estimated to be 16–21 million km². The global permafrost region, i.e. the exposed land surface below which some permafrost can be expected, is estimated to be 22 ±3 million km². A large proportion of this exhibits considerable topography and spatially-discontinuous permafrost, underscoring the importance of attention to scaling issues and heterogeneity in large-area models.

REFERENCES
9.4

Ice core based climate reconstruction of the Mongolian Altai

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In summer 2009 a 72 m ice core (56 m weq) reaching bedrock was drilled on Tsambagarav glacier in the Mongolian Altai (4140 m asl, 48°39.338’N, 90°50.826’E). The glacier temperatures ranging from -14.5 to -12.5°C indicate well-preserved paleoclimate records, suitable for climate reconstruction. Dating of the ice core was performed using four independent techniques, annual layer counting, identification of nuclear bomb as well as volcanic horizons, and nuclear dating with \textsuperscript{210}Pb and \textsuperscript{14}C (Jenk et al. 2009). The upper 36 m weq contain the last two centuries with high resolution. The lower 20 m weq are characterised by a strong thinning of annual layers, with an age of 5500 years BP near bedrock suggested by the \textsuperscript{14}C method.

Analyzed species are stable isotopes (\delta^{18}O) and major ions by using standard analytical techniques such as mass spectrometry and liquid ion chromatography. The ion records allow reconstructing the air pollution of the Mongolian Altai, whereas \delta^{18}O is assumed to be a temperature proxy. Former studies at Belukha glacier in the Siberian Altai showed a strong correlation between solar forcing and temperature in this region for the period 1250 to 1850 AD (Eichler et al. 2009). The Tsambagarav ice core will be used to investigate this findings and for a better understanding of the regional climate.

Occurrence of ice lenses in the upper part indicates melting in summer. This is confirmed by depletion of sulfate in the upper 10 m, due to relocation by percolating melt water. With increasing depth the occurrence of ice lenses declines, pointing to climatic changes during the last decades. The melt percent deduced from ice lenses is another potential temperature proxy (Henderson et al. 2006) and will be used combined with the \delta^{18}O for regional temperature reconstruction.

REFERENCES


9.5

Recent glacier changes in the Alps in response to atmospheric warming: Observations and consequences

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The past two decades have seen massive loss of glacier volume in the Alps as a reaction to a sudden temperature increase of about 1 degree in the 1980s. Indirect signs of glacier downwasting (e.g. emerging rock outcrops, split of tributaries, disintegration) can be followed on satellite imagery over the entire Alps. Latest data from 2009 indicate a continuation of previous negative trends with strong changes now also observed for the larger glaciers. In particular the development of new lakes at the terminus is a widespread phenomenon that enhances ice melt. For an assumed further increase in temperature in the coming decades, glaciers will continue to shrink and lose mass at an accelerated rate due to positive feedbacks. For example, when the glacier surface comes to lower elevations due to the downwasting, glacier melt will further increases.

Modelling of glacier beds with a simplified approach revealed several interesting aspects for further glacier evolution. For example, the bed topography of the largest glaciers is less inclined than the surface, for some glaciers the slope is in some sections even close to zero. This implies that these glaciers cannot retreat to higher elevations to come in balance with a warmer climate and will completely lose their tongues. Furthermore, most glacier beds show several overdeepenings of partly considerable size that might transform to lakes in the future. Such lakes might compensate for the loss of glaciers from a touristic point of view, but they might also increases the hazard potential in some regions. For hydro-power companies the vanishing of glaciers and the appearance of new lakes has important consequences for their long-term planning.

9.6

Subglacial Controls of the Short Term Dynamics at the Margins of the Greenland Ice Sheet: Interaction between subglacial water pressure and ice deformation

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With the aim of a better understanding of the processes responsible for peripheral thinning and seasonal flow velocity variations of the Greenland Ice Sheet (GrIS), we drilled 12 boreholes to bedrock during a field campaign this summer. The boreholes are located at two sites in the marginal area of the GrIS, downstream of SwissCamp.

In four boreholes, a newly devised borehole sensor systems, DIBOSS, was installed. DIBOSS is a digital borehole sensor system consisting of multi-sensor units (pressure sensor, inclinometer, magnetometer, thermistor), operated through a digital bus over a special extendable cable. It allows us to monitor subglacial water pressure, ice temperature, and shearing/stretching deformation of the ice body.

To get a comprehensive picture on the dynamics of the marginal areas also different surface measurements, e.g. surface velocity, complete the unique set of measurements.

We will present new data on the interaction between subglacial water pressure and ice deformation on the GrIS. We will also show data from pump tests which elucidate the development of the local subglacial hydrology.
9.7

Using miniature temperature loggers for the analysis of snow cover distribution and melting

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Mountain areas are characterised by an extreme lateral variability in elevation, exposure to solar radiation and ground material. This causes large differences in the seasonal snow cover distribution, snow melting and associated sub-surface phenomena such as ground temperatures and melt water infiltration. Because conventional techniques such as single point measurements of temperature or remote sensing are limited in the ability to reveal the spatio-temporal behavior at the snow-ground interface, this study investigates snow cover and snow melting based on spatial clusters of temperature measurements. Results are based on campaigns near Piz Corvatsch in the upper Engadin, Eastern Switzerland where ground surface temperatures (GST) were measured with miniature temperature loggers (iButtons) at 40 different locations, so called footprints. At each footprint up to 10 iButtons have been distributed randomly, measuring GST every 3 hours for 2 years. The footprints represent elevations of 2100 – 3300 m a.s.l.; aspects North, South, East, West and Slopes of 0 – 55°.

From a single temperature time series, two points in time are detected in a robust and precise way: The beginning of an isothermal snow pack, which also is the first time in the spring season when surface runoff is created, and the end of the snow cover. Furthermore (cf. Gubler et al. 2011), mean annual ground temperatures are calculated. For these three derived quantities, both the intra-footprint variability based on 10 measurements within 10 m x 10 m and the inter-footprint variability based on the comparison of values aggregated over footprints are analyzed and their patterns compared between measurement years.

Results provide important data for the validation of models and, especially though the analysis of considerable intra-footprint variability, point to the possible scaling conflict when comparing gridded models with single point measurements.

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9.8 Seismological Experiments on the Greenland Ice Sheet

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A critical gap in our current understanding of glaciers and ice sheets is how high sub-glacial water pressure controls the coupling of the glacier to its bed. Accordingly, some models predict that the Greenland Ice Sheet will lose ice in an accelerated manner through a feedback effect: High melt rates at the surface provide melt water which is routed through the sub-glacial drainage system and reduces basal friction, leading to high ice flow velocities and surface draw-down. This effect might induce a rapid decay of the ice sheet, and consequently contribute to global sea level rise.

In this context, the recent episodic increase of Greenland’s ice discharge to the ocean (e. g. Rignot and Kanagaratnam, 2006) has received much attention and raised concerns about ice sheet stability in a warming climate. Although observations indicate that an increase in ocean temperatures triggered this event (e. g. Holland et al., 2008), correlation between ice discharge and surface melt has been observed in the past (Rignot et al., 2008). Furthermore, it is not clear how land-terminating portions of the ice respond to increased surface melt. The ice sheet’s subglacial drainage system certainly plays an important role. Yet the question whether it will help enhance or diminish ice flow is currently subject to debate (e. g. Parizek and Alley, 2004; Sundal et al., 2011).

In order to better understand Greenland’s subglacial drainage system and its role in ice flow, we conducted a series of seismological and glaciological experiments on the ice sheet in the summer 2011. In an international collaboration, over a dozen boreholes were drilled to the glacier bed at two sites and equipped with scientific instruments to measure englacial deformation, temperature, basal water pressure and glacier sliding rates. Another project component was the installation of an unprecedented high-density seismometer array around one of the drill sites. With an aperture of about 1.5 km, the array consisted of 17 seismometers, including three deep borehole seismometers (up to 400 m deep) and two broadband stations. The goal of this network is to detect englacial dislocation processes (icequakes) indicative of hydrofracturing and stick slip motion. In combination with the borehole geophysical measurements, the seismic monitoring will thus elucidate the effects of changes in the subglacial drainage system on glacier motion and ice fracturing.

We will describe the seismological experiment focusing on practical challenges of deploying seismometers in direct contact with glacier ice. We will also give a first impression of the icequake waveform variety, which we have recorded. As expected from previous studies of Alpine icequakes we recorded a large number of surface crevassing events. However, we also detected deeper fracture events, providing indications for englacial hydrofracturing. The high-quality waveform data allow for determination of important source parameters, such as hypocentral location, fracture volume, fault plane orientation and stress drop.

REFERENCES
Radiocarbon dating of glacier ice

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In paleoclimatological investigations of ice cores from high-alpine glaciers dating is a non-trivial task mainly due to the complex impacts of glacier flow, accumulation, ablation etc. resulting in a strongly non-linear depth-age relationship. Particularly in the deepest parts of the ice core where thinning of the annual layers does not allow for conventional dating using annual-layer counting on seasonally varying parameters, other techniques are needed to establish precise age-depth models.

A novel radiocarbon method for dating ice cores has been developed by our group recently, utilizing carbonaceous particles contained in the ice. (Sigl et al., 2009). Carbonaceous particles are extracted from the ice samples via filtration prior to a combustion step where the fractions of organic carbon (OC) and elemental carbon (EC) are separated (Szidat et al., 2004). By means of the compact radiocarbon system MICADAS with a gas ion source (Ruff et al., 2007) gaseous CO2 samples from the combustion step are directly measured. This method proved to be applicable to high-alpine ice cores from the mid- and low-latitudes (e.g. Colle Gnifetti, 4450 m a.s.l., Swiss Alps; Nevado Illimani, 6300 m a.s.l., Bolivian Andes) resulting in ages covering a time-span from 1,000 to >10,000 years for both areas (Figure 1).

Applying this method to ice samples from various glaciated areas from the tropics to the poles yielded many interesting age estimations of these ice masses. Recently a 14C-based age-depth record was established for an ice core from the Mongolian Altai indicating a basal age of around 6000 years BP. Still, there are phenomena such as potential reservoir effects inherent in the carbonaceous aerosols which need to be better understood in terms of e.g. age offsets for the respec-
Failure of wet snow

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Liquid water changes the properties of snow in a highly non-linear manner and thus complicates the processes that lead to wet-snow avalanche formation. In previous studies, researchers investigated the influence of liquid water on the mechanical properties of snow in field studies (e.g. Brun and Rey, 1987; Bhutiyani, 1994). Since the reproducibility of field experiments is impaired by spatial and temporal variability of the snow, terrain, and weather conditions, systematic experiments under laboratory conditions are needed. The objectives of this study were to conduct first wet-snow experiments in a cold laboratory, test the experimental setup and gain primarily qualitative insights into the mechanical failure behavior of wet snow.

With a force-controlled loading apparatus (Reiweger et al., 2010) natural, homogenous snow samples, i.e. without a prominent weak layer, were loaded to about ~75% of the dry-snow strength. In this way we achieved a critical state prior to the wetting. Using a tube network, water with 0°C was conducted to the top of the snow sample. The loading process was digitally recorded and the resulting stress at failure was compared to water content measurements. Two displacement sensors measured the horizontal and the vertical displacement of the upper sample holder and a displacement field for the whole snow sample was obtained by Particle Image Velocimetry (PIV). In addition, acoustic emissions were recorded as well and were supposed to act as a real-time monitoring system for crack formation processes in the material.

We carried out 24 experiments. A set of results for one experiment is shown in Figure 1. The loading apparatus was suitable for wet snow experiments, however, the tube network was not sophisticated enough to simulate natural precipitation or melting conditions. An average water content slightly larger than 6% by volume was measured at failure, the variance was substantial, though (Figure 1a). Results agree very well with previous findings. With 6% by volume water exists in continuous paths throughout the pore space and thus destroys bonds between the grains. Wet samples failed at an average critical stress $\sigma_{\text{c,w}} = 4.6 \text{ kN m}^{-2}$ which was about a factor of 2 lower than for the same dry sample. Again these

References


findings are in good agreement with those obtained by Bhutiyani (1994). The acoustic activity increased significantly during loading and a certain time before failure during water infiltration (Figure 1b) indicating that percolating water is very efficient in breaking bonds between snow crystals. PIV analysis showed that wet snow allowed much more deformation before failure and rather collapsed than fractured with a recognizable pattern compared to dry snow (Figure 1c).

The experimental setup is in general suitable; nevertheless the setup has to be optimized for recording water content and controlling the water influx.

Liquid water clearly influences the snow microstructure and alters the failure behavior. Water decreases the strength of the snow sample by a factor of 2 which leads to a pronounced collapse failure instead of a shear fracture (dry snow).

![Graph](image)

**Figure 1:** (a) Vol. liquid water content ($\theta_w$) recorded with two TDR-probes ($\theta_{w,TDR1+2}$) and calculated using influx data ($\theta_{w,w}$) during experiment 19. Sample failure was at $t = 142$ seconds (red dashed line). (b) Acoustic emissions: typical example of cumulative count activity for experiment 19. Pink dashed line marks the end of loading and start of wetting, red dashed line marks failure of the sample. (c) Evolution of displacement field produced with PIV. 1 is showing the beginning of the experiment, 4 the last picture before failure of the wet sample. The red arrow is a reference arrow with constant length and direction; units are in pixel size (1 pixel $\approx 0.18$ mm).

**REFERENCES**


On the reliability of indicator path avalanches for local avalanche forecasting

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Still today we cannot reliably predict the occurrence of snow avalanches at the local scale, e.g. for a section of a transportation corridor. As avalanches are clear signs of instability, they are often considered as the best predictor for further events. In fact, avalanches that release at the beginning of a period with high avalanche activity, are called indicator path avalanches by avalanche professionals as they indicate a high probability of further avalanche events in that specific area. In the present work, we will check whether such indicator path avalanches exist and whether they can be used to improve local avalanche forecasting.

Long-term avalanche occurrence data for three areas in Switzerland, namely the Urseren valley in canton Uri as well as for Davos and Zuoz in the Canton of Grisons are analysed. We focus on avalanche paths where avalanches frequently occur, which may have the potential to act as precursors. We define an avalanche path as indicator path, if the majority of all avalanches in the surrounding region release at the same day or on one of the consecutive three days. Releases on the days before would decrease the value of a typical indicator path avalanche. In the region of Davos, the Salezer Tobel avalanche with a return period of about one year was found to have a certain precursor function, but only if it is of a certain size (Figure 1). The return period of these large-sized avalanches is five years. In the Urseren valley which runs about west to east from Realp to Andermatt, two indicator path avalanches were found: the Böschenlaui on the northern slopes of the valley and the Lochtal-, Lauital- and Spitzegglaui avalanches on the southern slopes. These three avalanches can be grouped to one single precursor avalanche as they have similar aspect, incline and length. In the community of Zuoz, in the Upper Engadine valley, four adjoining avalanches were considered and analyzed as a single indicator path avalanche. All these four avalanches with precursory function are characterized by heavy precipitation before or during the event, in most cases in combination with strong wind.

Even if indicator path avalanches can predict other avalanches to follow, the quality of the forecast remains poor. Whereas there is a good chance that the release of an avalanche in an indicator path is followed by other avalanches, there are too many situations when some of these avalanches release but not the one in the indicator path. To sum up, based on our analysis, it seems not feasible to forecast other avalanches simply based on the avalanche occurrence in an indicator path.

Figure 1. (a) Number of avalanches recorded in the surroundings of Davos on the 3 days before, on the day and during the 3 days after the Salezer Tobel avalanche run to an elevation of 1700 m a.s.l (blue) and 1800 m a.s.l. (b) Length distribution of the avalanches recorded in the surroundings of Davos on the 3 days before, on the day and during the 3 days after the Salezer Tobel avalanche occurred. Boxes show interquartile range, black lines the median, whisker 1.5 times the interquartile range and open dots indicate extreme values. Red dot indicates median length of the Salezer Tobel avalanche. Blue solid line shows the new snow depth within 24 h, dashed blue line the 3-day sum of new snow.
Past and future glacier changes in the western Nyainqentanglha Range on the Tibetan Plateau

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Glaciers are characteristic elements on the Tibetan Plateau and are contributing to its water resources. The glaciers receded throughout the region during the last decades with few exceptions only. This shrinkage has not only caused an increase in runoff, but contributed also to the measured increase in lake levels which caused flooding of pastures. Knowledge about past and future glacier changes is therefore essential to understand the mechanisms and the importance of glacier runoff in the hydrological cycle.

We quantify these changes for the western Nyainqentanglha Range (Figure 1). The study region is located in the southeastern centre of the Tibetan Plateau and is of special interest for glacio-climatological research: The region is influenced by both the continental climate of central Asia and the Indian Monsoon system and is situated in the transition zone between maritime and continental type glaciers.

The approach to determine past and model future changes requires multi-temporal satellite imagery, digital elevation models (DEMs) and representative time series of climate data. In a first step, a glacier inventory for the entire mountain range for the year ~2000 was generated using semi-automated remote sensing and GIS techniques based on Landsat ETM+ and SRTM3 DEM data. Furthermore, satellite data from Hexagon KH-9, Landsat MSS (year 1976), and Landsat TM/ETM+ (1991, 2001, 2005, 2009) were used to assess past changes through time.

The modelling of future glacier changes is based on two inputs: glacier elevation change in the past and a modelled glacier bed. A core element of the approach is the assumption that the thickness loss observed for the period 1970 – 2000 (by differencing the SRTM DEM from a DEM based on topographic maps) will continue in a similar way in the future. When future thickness change reaches the glacier bed, the respective part of the glacier area is removed in the model. Glacier thickness is estimated based on a mean basal shear stress for each glacier (derived from its elevation range) and local thickness values derived from an averaged surface slope angle (Linsbauer et al. 2009). Both information layers served as an input for a Geographic Information System (GIS) that is used to spatially extrapolate the local ice thickness values within the limits of the glacier. The results are calibrated and evaluated with direct thickness measurements and cumulative mass balance values. The latter are either derived from direct measurements or modelling on Zhadang Glacier, using climate data from surrounding stations and modelled climate data.

The entire western Nyaiqentanglha Range contains about 960 glaciers covering an area of . The glacier area decreased by 6.0 ± 3.0% from 1976 to 2001, which is less than presented in previous studies based on topographic maps and Landsat data. However, the shrinkage rate increased in the period from 2001 to 2009 (Bolch et al. 2010). The ice thickness model gives a mean ice thickness of about 30 m in the year 2000 and the DEM comparison reveals an average thickness loss of 0.3 m/a with an increasing rate in recent years. At these rates the glacier will certainly survive the 21st century. The modelling of future glacier thickness is under way and results will be presented based on different climate change scenarios.

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P 9.3

Effects of subsurface lateral water flow on soil thaw

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The effects of lateral water flow on the spatial distribution of depth of thaw in permafrost grounds have rarely been investigated with models. The GEOtop model, which solves the soil energy and water budgets in a coupled way and accounts phase change, has been here used to better understand how soil moisture spatial differences in the unfrozen upper part of the ground affect the thawing soil energy balance in an idealized hillslope topography. Results show that, in terrains with thermal conductivity highly variable with soil moisture, like organic soils, wetter areas absorb more efficiently heat from the atmosphere and, consequently, exhibit deeper thaw than drier areas. On the other hand, if thermal conductivity less markedly depends on soil moisture, as in mineral soils, the result is the opposite, since the effect of the higher thermal capacity resulting from higher soil moisture prevails.
P 9.4

Ice volume distribution in the Mauvoisin region and implications on glacier fluctuations

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Profound knowledge of the ice volume distribution in a catchment is an important prerequisite for various glaciological applications. Different approaches, such as volume-area scaling relations, radio-echo soundings or borehole measurements, allow the determination of the ice volume with different levels of precision. In the Mauvoisin region, Valais Alps, five larger glacier (surface area between 5 and 18 km²) and several smaller glacier are found, which made up a total glacialized area of about 65 km². Extensive helicopter-borne ice radar measurements were carried out in this region in spring 2011. Almost 150 km of radar profiles were recorded. In order to obtain a continuous digital elevation model of the glacier bed topography, the information from the radar profiles has been integrated in the approach of Farinotti et al. (2009). First results indicate a total ice volume of about 4 km³ and a maximal ice-thickness of more than 250 m. We assessed the detailed changes in ice volume distribution and glacier geometry until the end of the 21st century by using the glacio-hydrological model GERM (Huss et al., 2008, Farinotti et al., in press) which is constrained by the most recent climate scenarios of C2SM (Bosshard et al., 2011). Extensive glacier retreat is projected independently of the scenario chosen. Smaller glaciers will disappear in the next decades. Only larger glaciers having substantial ice masses located at high elevations, will be partly left by 2100.

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P 9.5

Integration of glacier databases within the Global Terrestrial Network for Glaciers (GTN-G)


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Changes in glaciers provide one of the clearest evidence of climate change and as such they constitute an Essential Climate Variable in the Global Climate/Terrestrial Observing System (GCOS, GTOS) in support of the United Nations Framework Convention on Climate Change (UNFCCC). As recommended by the International Council for Sciences (ICSU), free and unrestricted international sharing of high-quality, long-term and standardized data and information products is one of the basic requirements for advances in research as well as for political decisions.
The internationally coordinated collection and distribution of standardized information about glacier changes was initiated in 1894 and is today coordinated within the Global Terrestrial Network for Glaciers (GTN-G) under the auspices of FAO, ICSU, UNESCO, and WMO. The GTN-G is jointly run by three operational bodies involved in glacier monitoring: the World Glacier Monitoring Service (WGMS, www.wgms.ch), the U.S. National Snow and Ice Data Center (NSIDC, www.nsidc.org), and the Global Land Ice Measurements from Space (GLIMS, www.glims.org) initiative.

With an online service (www.gtn-g.org), GTN-G provides fast access to regularly updated information on glacier distribution and changes. Currently, this includes glacier inventory data from about 100,000 glaciers mainly based on aerial photographs and maps, as well as digital outlines from about 100,000 glaciers mainly based on satellite images, length change series from 1,800 glaciers, mass balance series from 250 glaciers, geodetic thickness or volume changes from 430 glaciers, information on special events (e.g., hazards, surges, calving instabilities) from 130 glaciers, as well as 13,000 photographs from some 500 glaciers. In addition, for a number of 26 glaciers, fluctuation series (going back to the 16th century) are available as reconstructed from moraines, photographs, paintings and written documents. All of these datasets are freely available and have been used in numerous scientific publications as well as in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC).

P 9.6
“Old-fashioned” photogrammetric analyses – still a key tool for the reassessment of long-term glacier changes: examples from Storglaciären, Sweden

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At Storglaciären, located in the Kebnekaise massif in northern Sweden, aerial photographs have been taken at decadal intervals since the beginning of the mass balance monitoring program, which was started in 1945/46. Early studies used the resulting vertical photographs to produce glaciological maps with which the in-situ observations could be verified. However, these maps as well as the derived volume changes are subject to errors which resulted in major differences between the derived volumetric and the glaciological mass balance. In this study, we reanalyzed dia-positives of the original aerial photographs of 1959, -69, -80, -90 and -99 based on consistent photogrammetric processing. From the resulting digital elevation models and orthophotos, changes in length, area, and volume of Storglaciären were computed between the survey years, including an assessment of related errors. Between 1959 and 1999, Storglaciären lost an ice volume of 19x106 m³, which corresponds to a cumulative ice thickness loss of 5.69m and a mean annual loss of 0.14 m. This ice loss resulted largely from a strong volume loss during the period 1959–80 and was partly compensated during the period 1980–99. As a consequence, the glacier shows a strong retreat in the 1960s, a slowing in the 1970s, and pseudo-stationary conditions in the 1980s and 1990s. In addition, we compared the calculated volumetric mass balances with the in-situ measured mass balances and were able to reassess the data series. The resulting data and findings promote the importance of aerial photographs in glacier research, especially for cross-checking in-situ measurements.
P 9.7

Ice thickness distribution of 90’000 mountain glaciers around the globe using the GLIMS database and SRTM/ASTER DEMs

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Mountain glaciers and small ice caps are expected to contribute significantly to eustatic sea level rise over the next decades. The ice volume of these more than 100’000 glaciers is normally estimated using volume-area scaling relationships (e.g. Bahr et al., 1997). Volume-area scaling does, however, not account for the characteristics of individual glaciers, and does not yield any information about the spatial distribution of the ice thickness which is required e.g. for the transient modelling of glacier ice flow dynamics. The GLIMS glacier database essentially provides 2D information about an important fraction of mountain glaciers and small ice caps on the earth. This study proposes and applies a method for adding the third dimension to glacier inventory data by inverting global digital elevation model (DEM) data to distributed ice thickness. This allows inferring additional glaciological variables that are vital for assessing the future retreat of glaciers around the globe and their contribution to sea level rise.

The method to estimate ice thickness distribution is based on glacier mass turn-over and the principles of ice flow mechanics. Using glacier elevation bands evaluated from a digital elevation model, volume balance flux is calculated and transformed into an initial guess of the local ice thickness using Glen’s flow law (similar as in Farinotti et al., 2009). In an iterative procedure, the basal shear-stress distribution and the shape factor is determined along the glacier until convergence is reached. Finally, mean thickness in each elevation band is extrapolated transversal to the topographic gradient including local surface slope. Thus, for each glacier ice thickness on a regular grid can be calculated (Figure 1). The only input requirements are a glacier outline (given by the GLIMS glacier database) and a DEM.

DEMs between 60°N and 60°S are available from the Shuttle Radar Topographic Mission (SRTM) with a spatial resolution of about 90 m. North and South of 60° the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) DEM (30m resolution) is used.

Based on these readily available data sets, thickness distribution and ice volume of all mountain glaciers of the GLIMS data base is evaluated. Inferred thickness distribution is validated against in-situ measurements (radio-echo sounding) on about two dozens alpine glaciers, and against additional ice volume data indicating a good agreement with field data (r²=0.83). The calculated ice volume of about 90’000 mountain glaciers evaluated using the presented method results in a total ice volume of 26’400 km³. Further research is required to better estimate the accuracy of the method for different mountain ranges and to overcome the many uncertainties arising from inhomogeneous elevation models or glacier inventory data.

Figure 1. Calculated ice thickness distribution of Malangutty Glacier, Karakorum, 36°N 75°E.
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P 9.8
Numerical simulation of the Young's Modulus of snow
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Snow is a porous, sintered material consisting of ice and air. As a highly metamorphic material its microstructure i.e the ice skeleton permanently restructures which leads to a great variability of snow types and thus to a great variability of mechanical properties. In literature the Young's modulus is empirically related to snow's density, neglecting microstructural information. With 3D images of the snow microstructure obtained by computer tomography we made voxel-based finite element calculations of the Young's modulus. For different snow types of the same density the Young's modulus can vary up to a factor of five, which can also be seen in our results. We also found that the size of the representative elementary volume (REV) for the Young modulus depends on the snow type and is, in general, much larger (up to a factor 3) than the REV for geometrical properties like density or specific surface area. Furthermore, we show that certain snow types exhibit a highly anisotropic elastic behaviour. Our results underline the importance of the microstructure of snow. At the current stage of our experiments, it remains to be seen if basic geometric descriptors of microstructure, as density (porosity) and specific surface area, are sufficient to correlate Young's Modulus uniquely.

P 9.9
The Swiss Alpine Glacier’s Response to the “2 °C air temperature target”
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Limiting global mean temperature increase to 2 °C (‘2 °C target’) is a major topic in the international climate debate. The effective impacts of a 2 °C temperature increase on regional scale systems like mountain glaciers, however, have yet received little attention.

Here, we combine homogenized long-term meteorological observations and Regional Climate Model (RCM) simulations to construct a plausible 2 °C warming scenario for the Swiss Alps. While the 2 °C target refers to a global average, a more pronounced climatic change in the Swiss Alps (Begert et al., 2005) has to be considered. Climate model output of the Alpine 2 °C scenario is then used as direct input for a glacier mass balance and glacier retreat model (Machguth et al., 2009; Huss et al., 2010). Distributed mass balance, glacier volume and area change is computed for the time span 1970 to 2150 and for 101 glaciers, representing about 50% of the glazierized area and 75% of the ice-volume in Switzerland.
The direct coupling of gridded climate scenario data to the distributed glacier mass balance model implies new challenges in model calibration. Furthermore, the experiment is challenging because both glacier retreat and subsequent adaption of the glaciers to a new climate is modeled.

In our study, the Alpine 2 °C temperature target is reached at around 2045. From this point on no further warming occurs and glaciers adapt at various pace to the new climate: smaller glaciers reach a new equilibrium around 2080 to 2100 while the mass balance of the largest glaciers becomes zero only around 2140 to 2150. The different response times result in a characteristic curve of glacier volume and area loss: a phase of pronounced decrease ends around the year 2090 and is followed by reduced volume loss and eventually full stabilization. Relative to the year 2000 and after full adaption in the year 2150, glacierized area and runoff are both reduced to about 45% while ice volume falls to about 25% (Figure 1).

Figure 1. Model output for all 101 glaciers: (a) runoff; (b) volume, (c) mean mass balance and mass balance for Lang and Aletsch glacier (d) area.

The direct use of gridded RCM scenario is regarded as a step forward in the modeling of glacier change scenarios. Relevant feedback processes in glacier retreat like the mass balance-surface height feedback and the albedo feedback are considered. Modeled adaption times of glaciers agree well with previously estimated response times for the Swiss Alps (Haeberli and Hoelzle, 1995). The model output provides for the first time a detailed assessment of expected changes in Alpine glaciati-on under a global 2 °C warming.

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Stability information supplied by the snow cover model SNOWPACK

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The one-dimensional snow cover model SNOWPACK (Lehning et al., 1999) simulates snow stratigraphy using input data from automatic weather stations. The model provides information on the snow conditions reproducing most of the physical processes affecting the snow cover. For avalanche forecasting direct information on snow stability is most wanted. Lehning et al. (2004) introduced three stability indices, namely the natural stability index ($S_N$), the skier’s stability index ($S_{SK}$) and the deformation index ($S_d$). They are mostly based on the shear strength of snow. Schweizer et al. (2006) modified the $S_{SK}$ by introducing two parameters (difference in grain size and in hardness) which are related to snow stratigraphy (SSI). Further, they developed a classification, based on the SSI and $S_{S3a}$ that assigns a stability class (poor, fair, good) to simulated snow profiles (stability class index).

Schirmer et al. (2010) compared the characteristics of simulated and observed weak layers with observed stability conditions using the SSI to select the potentially most critical weak layer within a simulated snow profile. Based on their statistical analyses they concluded that SNOWPACK is useful to estimate snow stability. However, they noted that the relation of some weak layer properties to snow stability was counterintuitive and contrary to previous results derived from analysing manually observed profiles. Other analyses (e.g. Monti et al., 2009) did not find this discrepancy. The objective of the present work is therefore to solve the problem of these contradicting findings.

Picking the weak layer with the help of the SSI proved to be the most crucial step in estimating snow stability. We compared various versions of SNOWPACK and the corresponding implementation of SSI. In fact, with the presently implemented version, the SSI has in about 40% of the cases difficulties in finding the potentially most critical weak layer (Figure 1). Using the same data as Schirmer et al. (2010), but excluding all cases where we were sure that the weak layer was not detected correctly, we found that most weak layer parameters were either not related with stability, or the relation was not statistically significant. Integrating the simulated shear strength instead of the hand hardness index improved the discrimination power of the SSI. Based on our analyses, we suggest to recalibrate the SSI and/or to introduce a new method for assessing snow stability from simulated snow stratigraphy. The process of weak layer picking and the evaluation of its strength have to be separated. In any case, the new method must be robust against changes with in the modelling framework – otherwise repeated recalibration is needed.

Figure 1: Comparison of the SNOWPACK simulations (winter 2001-2002) for the Weissfluhjoch study plot, used by Schweizer et al. (2006) and Schirmer et al. (2010). In the case of Schirmer et al. (2010), the SSI (green line) identifies the weak interface just below the depth of ski penetration from about the mid of December 2001 to the mid February 2002. Throughout this period, the depth indicated by the SSI is most probably not the depth of a truly critical weak layer. Therefore, these layer properties should not be used for the statistical analyses.
Overcooled talus slopes are porous debris accumulations located in mid-latitude areas far below the regional mountain permafrost limit. These landforms are characterized by the occurrence of a negative thermal anomaly compared to the mean annual air temperature (MAAT) in the lower part of the slope, the preservation of ground ice during summertime and often by the existence of boreo-alpine species at elevation where MAAT is definitively positive. The main process leading to these cold environments is an internal and reversible mechanism of air circulation, the so-called “chimney effect” (Morard et al. 2010).

Since 2004, temperatures at the ground surface and in boreholes were recorded continuously in several sites in western Switzerland to better understand the ventilation process. In addition, the use of time-lapse electrical resistivity tomography (ERT) was used to document indirectly more precisely the 2D spatial pattern of temperature changes at depth (Hilbich et al. 2008).

The main results of this multi-methodological approach are:

- Despite differences in elevation, orientation, vegetation cover and material properties, the same seasonal thermal regime was observed in all the investigated sites. In the lower part of the talus slopes, a negative annual thermal anomaly reaching 3 to 7°C compared with MAAT is observed. This anomaly tends to increase at lower elevation. In contrast the upper part of the slope is characterized by a positive annual thermal anomaly.

- During wintertime, resistivity increases strongly (about 4 to 20 times) at the ground surface in the lower part of the talus slope, as at depth in the lower half of the debris accumulation. These modifications fit well with temperature records in borehole (figure 1). They illustrate both the deep penetration of freezing and the (re)filling of a cold reservoir inside the porous talus slope.

- The thermal conditions observed at the ground surface and in the shallow sub-surface in the blocky layer are mainly influenced by the intensity of winter cooling. The size of the cold reservoir is for instance more important during winters with cold atmospheric conditions. Winter air temperature is thus the main controlling factor for the evolution of the thermal regime of ventilated talus slope. However snowcover and summer temperatures play a less significant role.

- According to the observations of two boreholes in Dreveneuse d’en Bas (Valais Prealps, 1590m a.s.l., MAAT +4°C), a thin talus permafrost forms just a few meters below the surface in the lower part of the slope. This frozen ground extends to greater depth until the middle part of the slope, where it is found at 11.5m depth directly beneath the blocky material in finer sediments (till). This advective-induced permafrost is mainly temperate and its geometry and occurrence have suffered very rapid changes since November 2004: responding directly to contrasted interannual winter air temperature conditions, its growth has been reported between 2004 and 2006 and its thaw consecutive to the exceptional mild winter 2007. Only seasonal freezing was observed in 2008 and 2009. The little snowy but cold winter 2009-2010 led to the rebuilding of this particular extra-zonal permafrost.
Figure 1. Resistivity – temperature relationships in the ventilated overcooled talus slope in Dreveneuse d’en Bas (Valais) (right: mean value).

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P 9.12
Surface Nuclear Magnetic Resonance Tomography on a First-Year Sea Ice Pressure Ridge

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The porosity of the keel of a sea ice pressure ridge is one of the critical parameters in order to understand the evolution of the Arctic sea ice cover, since it accounts for its vulnerability against melting. Sea ice pressure ridges are built when drifting ice floes collide due to convergent forces, i.e. due to ocean currents or winds. Breaking ice blocks inclose water-filled cavities in the keel of the ridge. The determination of the keel porosity with drillings is inaccurate, because it only yields information about a few investigated points. Since the porosity within the keel equals its liquid water content, surface-NMR can be applied, a method which is directly sensitive to unbound hydrogen protons.

My master thesis (and therefore my presentation) describes the first application of surface-NMR on sea ice. A surface-NMR tomography using seven coincident soundings is performed on a first-year sea ice pressure ridge on the land fastened ice off Barrow, Alaska. The inversion yielded the water content of the shallow part of the ridge, 31 ± 7%, and of deeper part, 49 ± 7% (see Figure 1).
The error range of 7% results from noise, but also from the uncertainty and the simplification of the ridge geometry, which was investigated with a synthetic modelling example. A further result of a preceding modelling study is the validation of the used numerical modelling algorithm for the calculation of the magnetic field induced by a transmitter loop at the surface.

The application of surface-NMR on sea ice is particular due to the high electric conductivity of the subsurface. The geometry of the ridge is known from drillings and yields, together with literature and the analysis of a drillcore, the conductivity distribution of the subsurface. The geometry and the conductivity distribution are successfully incorporated in the inversion of the surface-NMR data. Nevertheless, a misfit of around 30 nV (maximum amplitude around 200 nV) in the imaginary part of the sounding curves remains unexplained, giving rise to further research.

The presence of sea water on the one hand, and the absence of cultural noise due to the remoteness of the survey site on the other hand, yielded a very high signal-to-noise ratio. The good quality of the data allowed the demonstration of the effect of accounting for relaxation during the pulse (RDP). Neglecting RDP would lead to a severe underestimation of 8% water content within the deep keel. The incorporation of off-resonance effects in the forward modelling led to a reduction of 5.5 nV for the average misfit of the real part of the sounding curves.

Figure 1. Profile throughout the investigated sea ice pressure ridge showing the water contents of the different blocks in %. The ridge geometry is obtained by drillings, the water contents are estimated from seven coincident surface NMR performed with the 20x20 m loops L0 to L6.

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The first complete inventory of glaciers and ice caps for Eastern Greenland

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Meltwater from glaciers and icecaps (GIC) provide a significant contribution to global sea-level rise, but estimates are uncertain due to the globally still incomplete information about glacier location and size, as well as large uncertainties in current Global Climate Models (GCMs). Recent studies that calculate global sea-level rise from GIC have developed simplified approaches using information from glacier inventories or gridded data sets and different GCMs. However, for several strongly glacierized regions very rough assumptions about the ice distribution have to be made and an urgent demand for a globally complete glacier inventory data is expressed.

The GIC on Greenland are one of these regions. Within the „EU-funded“ project ice2sea we map the Eastern part of Greenland using Landsat ETM imagery acquired around the year 2000 and the ASTER GDEM to derive topographic parameters and drainage divides. Up to now more than 5500 GIC with a total area of about 26.000 km² have been mapped between 62° and 80°N considering only glaciers with an area larger than 0.1 km² that have no direct connection to the ice sheet.

The largest valley glaciers are often debris covered, whereas smaller and mountain glaciers are often shaded due to the steep topography. Seasonal snow hiding the real glacier perimeter is a problem in some of the scenes that can only be solved by using scenes with better snow conditions. The artefacts in the GDEM are locally rather severe, but for the GIC considered for this inventory they were manageable. A comparison with the outline of the Greenland ice sheet as used in current models revealed that along the eastern coast a considerable amount of the local GIC is included in the extent of the ice sheet.
P 9.14

Short-term velocity variations of an alpine cirque glacier

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Since the pioneering work of Lewis and colleagues at several small glaciers in Norway (Lewis 1960), cirque glaciers have held the ignominious distinction of being simple. Given that Lewis’ results predated modern glaciological theory, however, this reputation may be unwarranted. As part of a larger project designed to investigate the flow dynamics of West Washmawpta Glacier (Sanders et al. 2010), a small cirque glacier in the Canadian Rocky Mountains, we instrumented the ice surface with four GPS receivers mounted on metal conduit. Each receiver recorded its position once a day. We installed all four receivers in mid-May, when the glacier was still completely snow covered. When we returned to the glacier in early July, two of the antennas were still standing; the other two had tilted dramatically as a result of several meters of snowmelt. The average speeds of the four receivers over the course of the entire measurement period were between 6.2 and 8.0 m/yr. The highest average velocity occurred nearest the front margin of the glacier. The velocity record also shows three speedup events. We attribute the first and second speedup events to high water pressure at the glacier bed resulting from high melt rates. The third and final acceleration occurred immediately following one of the largest downpours of the summer season. The maximum speed reached at each receiver during this last speedup, which ranged from 18.1 to 20.1 m/yr, was the season high as well. We propose the development of an efficient subglacial stream network prohibited any further speedup events in the final month of the melt season, despite high temperatures and several rainstorms. Our results cast further doubt on the prevailing paradigm of cirque glacier behavior.

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P 9.15

Projection of permafrost evolution under climate change scenarios and evaluation of sensitive influencing factors

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Climate change as projected by contemporary global circulation and regional climate models will have a great impact on high latitude and high mountain permafrost. The impact of these changes for the time period of 1990 to 2100 has been evaluated for two characteristic high alpine permafrost sites using meteorological input of 6 different Regional Climate Models to drive a sophisticated one dimensional permafrost impact model. Statistical analysis of the modelled climate variables as well as the output of the impact model has been done to gain insight on the sensitivity of the active layer to changes in climate.

The projected snow cover at the two sites shows a general decrease in duration of about 50 to 80 days per year during the 21st century. Strong increases in active-layer thickness (ALT) of up to 100% can be seen at the sediment covered bedrock site Schilthorn followed by the formation of a talik around the year 2020 in most of the models. At the rock glacier site Murtèl the increase in ALT is less pronounced and the talik formation does not start until 2070. This thermal evolution is linked to an increase in unfrozen water content in the permafrost body at both sites.

Multiple linear regression analysis shows a strong dependence of ALT on ice content and summer soil surface temperatures and to a less significant degree on snow cover timing and duration. The ice content of the active layer in preceding years influences the ALT for about 3 to 7 years at both sites.
P 9.16

Monitoring temporal changes within the snowpack utilizing upward-looking radar systems

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As the seasonal snow cover exists close to its melting point, the snow structure is constantly changing. Furthermore, the snowpack is spatially variable. Therefore, the evolution of snow stratigraphy can only be followed if using a non-destructive, continuously operating sensor system. Such systems should provide information on snow layering, snow settling, i.e. strain rates for specific layers after recent loading by precipitation, or the propagation of a wetting front.

For this study, two different upward-looking radar systems buried in the ground recorded continuous data of snow stratigraphy during the winter season 2010-2011. Under dry-snow conditions every three hours a measurement was performed; as soon as parts of the snowpack were wet, the sampling rate was changed to two measurements per hour. In addition to a previously installed and tested upward-looking impulse radar system (upGPR) a low-cost self-assembled frequency modulated continuous wave system (upFMCW) in a similar frequency range was buried in the ground. We compare the radar signals gathered with two different frequencies (600, 1600 MHz) with the upGPR to the signals recorded with the upFMCW in the frequency range of 1 - 2 GHz. Under dry-snow conditions, the radar offers the unique possibility to follow the evolution of internal snow layers, in particular to monitor settling rates of single layers. Under wet-snow conditions, the occurrence of strong multiple reflections as well as the daily increase in two-way travel time of reflection horizons allow one to determine the absolute amount of liquid water, the depth of a wetting front, the timing of the daily peak in volumetric liquid water content and its decreasing due to refreezing during the night.
**Geophysical monitoring of three different permafrost forms within the Murtèl-Corvatsch Area, Upper Engadin**

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Permafrost in high mountain areas occurs in a great variation of surface and subsurface material and texture within short distances. Therefore, the thermal regime of the subsurface strongly depends on site-specific factors like the grain size, the pore volume and type of material beside climatic factors such as air temperature, incoming radiation and precipitation.

To fulfill a long-term aim, the analysis of the sensitivity of high mountain permafrost to climatic changes, an electrical resistivity tomography (ERT) as a regularly measured monitoring was installed. Performing geoelectrical measurements in permafrost regions implies that changes in the resistivity are due to different subsurface materials and to phase change processes of water/ice. A regularly monitoring of the subsurface allows to detect seasonal as well as annual changes of resistivity values and is therefore a useful method to analyse and predict the development of periglacial material. This poster presents two ERTM-data sets measured since 2009 for three different periglacial forms. It illustrates well the annual changes in the resistivity values and the different development of the active layer and the freezing front.

Two ERTM’s were installed (one during summer 2009 and the other in 2010). Both are situated within the well investigated Murtèl-Corvatsch Area (Haeberli, W. et al. 1988, Vonder Mühll et al. 2001), covering three different periglacial forms: bedrock, talus slope and rock glacier. To verify the ERTM-data, borehole temperature data (the ERTM-profiles are placed beneath two boreholes (Hanson, S. & Hoelzle, M., 2005)) was used and refraction seismic tomography (RST) was performed ones a year. For using the change of resistivity as an implication for changes in the water/ice content, the resistivity for the frozen and unfrozen state of each investigated material was measured and verified by the borehole temperature data. To analyse seasonal changes in resistivity, ERTM-measurement were performed every 2 months and to estimate the annual changes in resistivity values, the summer ERT-data as well as the RST-data (measured in mid-august) of each year were compared.

The analysis of the ERTM and the RST data of the last three years show strong differences depending on the material. Especially the development of the freezing front of both sites varies. Regularly and longterm geophysical observation e.g. by ERTM is a useful method to understand and predict permafrost development and a first step to analyze the sensitivity of periglacial material to climatic changes.

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Study of a new Svalbard ice core

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Svalbard is an archipelago north of Norway, surrounded by the Arctic Ocean. It ranges from 74 to 81°N and from 10 to 35°E and covers an area of 61022 km² of which 60% is glaciated.

Since the mid-1970’s ice cores have been recovered from Svalbard, but very few have been studied in detail. The main issue occurring was dating due to melting processes. However, Lomonosovfonna, the highest ice field in Svalbard, was suggested to have a better preserved stratigraphy and thus be less influenced by melting than other sites on Svalbard (Pohjola et al. 2002; Moore et al. 2005).

In 1997, a 121 m long ice core was drilled at Lomonosovfonna by an expedition organized by the Norwegian Polar Institute (NPI). This core was studied in great detail, providing a historical record for the pollution and climate on Svalbard back to about 800 years (e.g. Divine et al. 2011). Furthermore, this study corroborated the assumption of less affection of the Lomonosovfonna by melting (Pohjola et al. 2002).

In the last years, the interest in black carbon (BC) has increased due to its potential impact on Arctic warming and the retreat of glaciers (Hegg et al. 2009). So far, no historical record for BC exists from Svalbard. In order to obtain this record a new 149 m long ice core was drilled at Lomonosovfonna (78°49’24.4”N, 17°25’59.2”E; 1202 m a.s.l.) in spring 2009.

This study deals with that new Lomonosovfonna ice core, focusing on the historical record of BC along with the analysis of the stable isotopes (δ¹⁸O, δD), ³H and ²¹⁰Pb for dating purposes and other components related to climate variability and pollution such as Ca²⁺, Na⁺, K⁺, Mg²⁺, NH₄⁺, Cl⁻, CH₃SO₃⁻, NO₃⁻, SO₄²⁻.

The stable isotope record of the uppermost 2.6 m w.eq. (= four years) already indicated that the δ¹⁸O record shows a distinctive seasonal cycle with higher values attributed to summer snow. However, the concentration records of the chemical species tend to peak in winter/early spring in this uppermost core part which probably represents the Arctic haze phenomenon. The average ion concentrations were further found to compare well with long-term records from earlier ice core studies at Lomonosovfonna.

Moreover, the core is analyzed for BC with a single-particle soot photometer (SP2) to obtain a historical record that can then be compared to BC measurements from other Arctic sites such as Greenland, for example (McConnell et al. 2007).

Additionally, snow samples have been taken from several places around Longyearbyen and at Lomonosovfonna in March 2010. These samples have been analyzed for major ions as well as BC. In general, the concentrations of both major ions and BC are lower at Lomonosovfonna than at the other sampled sites. This can be explained by the greater distance to the potential sources, the sea or human activities, respectively, the latter being an important source for local BC pollution as already indicated by former studies.

REFERENCES
Temporal characteristics of various cryosphere-related slope movements in high mountains: GPS measurements and analysis

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Permafrost slopes are sensitive to climate change and permafrost degradation can develop or accelerate slope instabilities. With predicted global climate change, it must be anticipated that instabilities of rock slopes and movement of ice-rich debris will increase (Haeberli and Burn, 2002). Knowledge of processes and factors affecting slope instability is essential for detecting and monitoring potentially hazardous slopes. The overall aim of this study is to detect and characterize differing slope movements in alpine periglacial environments, in order to better understand the broad range of phenomena and processes encountered. The main study site (Matter valley, Switzerland) includes exceptionally fast rock glaciers as well as various slopes where clear evidence for movement, e.g. open fractures, exist. However, the underlying mechanisms of these movements and the importance of subsurface ice for them are largely unclear.

This study is part of X-Sense, a joint research project between different research groups (geodesy, computer engineering, remote sensing and geography). Within X-Sense, new low-cost GPS devices suitable for high mountain environments have been developed (Beutel et al., 2011). Based on these measurements, high-accuracy daily differential GPS-positions and the corresponding velocities are calculated. The novelty of obtained data is that they have a high temporal resolution and can cover several years. This makes it possible to identify both velocity variations (a) within a short period (e.g. week or season) and (b) between different years. The exact timing of acceleration can help to detect influencing factors, such as snowmelt.

The low costs per GPS-device allow measuring at many locations. The high number of measurement points, located upon various slope movement types, will help to find common characteristics of cryosphere-related slope movements in high mountains. Since December 2010, 15 GPS stations on moving features have been installed.

First results from two GPS-stations, show strong short-term velocity fluctuations in spring. The velocity of a potentially destabilized rock-glacier tongue was slowly decreasing during winter. From the end of April, with increasing air-temperature and the disappearance of the snow cover, velocities increased up to nearly 2 cm/day in the middle of May, but again decreased to ~1.5 cm/day. These results demonstrate the importance of continuous (here daily) measurements over longer periods and their potential to enable the inference of factors and processes controlling slope movement.

The next analysis will include a more quantitative comparison of GPS data from the different locations and meteorological data, using descriptive statistical methods. To increase process understanding, we will apply statistical methods to combine measured data with physically-based computer simulations.

REFERENCES
Glacier Laser-scanning Experiment Oberwallis: project overview and first results

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Glacier mass balance is widely accepted as a key parameter in hydrological and climate change research. Traditionally, the mass balance of a glacier is measured in-situ, at an annual or seasonal basis, using ablation stakes and snow pits and compared with decadal volume changes derived from photogrammetric analysis of aerial photographs. A major drawback in glacier photogrammetry is the lack of contrast in shady and snow covered (accumulation) areas. Since the 1990s, pilot studies have repeatedly shown that airborne laser-scanning has the potential to overcome these problems and can provide accurate elevation changes at an even higher spatial resolution.

In this three-year project (2009-2012) we investigate the ability of airborne laser-scanning (ALS) for operational use in glacier monitoring at Findelengletscher in the Valaisan Alps, Switzerland. ALS flight campaigns were carried out by BSF Swissphoto in October 2005, October 2009, April and September 2010. The area of interest extends over 27 km² and is sampled with a mean point density of more than two laser echoes per square meter. In addition to the geometrical data, the laser-scanning systems used (Optech ALTM 3100 and Gemini) provided as well intensity data for every return which can be used for surface type classifications and albedo modeling. The flight campaigns were coordinated with direct glaciological mass balance measurements that have been carried out since 2004/05 and are today jointly run by the Universities of Fribourg and Zurich.

The main project goals are to (i) assess the accuracy of the ALS digital elevation products, (ii) compare the glaciological and the geodetic mass balances including a detailed uncertainty assessment, (iii) evaluate the further use of the ALS products for glaciological and hydrological applications, e.g. in combination with airborne radar surveys and airborne push-broom imaging spectrometer, and (iv) visualize the scientific findings for educational purposes and public outreach products.

This presentation provides an overview on the present state of the “Glacier Laser-scanning Experiment Oberwallis” and discusses first results of the project (see e.g. Figures 1 and 2).

Figure 1. Virtual view of Findelengletscher, Valaisan Alps, Switzerland. The figure shows an overlay of the ALS elevation data from 2005 with an UltracamXP image mosaic from 2009.
Figure 2. Elevation change as derived from differencing the digital elevation models produced by the two ALS surveys of October 2005 and October 2009.