11. Cryospheric Sciences

J. Alean, A. Bauder, B. Krummenacher, J. Nötzli, C. Lambiel,
M. Lüthi, J. Schweizer, M. Schwikowski

Swiss Snow, Ice and Permafrost Society

TALKS:

11.1 Barandun M., Sold L., Huss M., Azisov E., Salzmann N., Usubaliev R., Hoelzle M.: Accumulation rates on Abramov Glacier, Kyrgyz Pamir between 2001 and 2013

11.2 Boffi G., Wieser A., Binder D., Schöner W.: GNSS-based monitoring of kinematic glacier surface deformation at the A.P. Olsen Ice Cap

11.3 Bosson JB., Lambiel C.: Current evolution of small glacier systems in alpine permafrost environments in relation with their internal structure

11.4 Braillard L., Delaloye R., Abbet D., Barboux C., Morard S., Staub B.: Onset and development of destabilization phases of rock glaciers in the Swiss Alps

11.5 Caduff R., Wiesmann A., Bühler Y.: Quantification and mapping of snow surface dynamics with terrestrial radar interferometry: From avalanche mapping to snow creep measurements

11.6 Capelli A., Kapil J. C., Reiweger I., van Herwijnen A., Schweizer J. , Or D.: Propagation characteristics of acoustic waves in snow under laboratory conditions

11.7 Comola F., Schaefli B., Rinaldo A., Lehning M.: Flow and Temperature Dynamics in the Hydrologic Response of Alpine Catchments: Travel Time Formulation and Geomorphologic Signatures

11.8 Gabbi J., Huss M., Bauder A., Schwikowski M.: The impact of Saharan dust events on long-term glacier mass balance in the Alps

11.9 Huss M., Dhulst L., Bauder A.: Ten new long-term glaciological mass balance series for Swiss glaciers

11.10 Langhammer L., Dunse T., Langley K., Isaksson E., Hagen J.O.: Deriving long-term firn stratigraphy from optical borehole camera measurements on Austfonna, Svalbard

11.11 Reiweger I., Gaume J., Schweizer J.: Failure Criterion for Weak Snow Layers

11.12 Sommer C., Mott R., Lehning M., Haussener S.: Variability of snow thickness changes in steep rock faces based on terrestrial laser scanning

11.13 Stawicki M., Magnusson J., Jonas T.: Sensitivity of operational snow melt predictions to different modelling setups

11.14 Werder M. A.: Fast ice flow, troughs, overdeepenings and subglacial hydrology

POSTERS:

P 11.1 Becker P.: Ice flow in the Alps during the last glacial maximum, a modeling approach

P 11.2 Capt, M., Bosson, J.-B., Micheletti, N., Lambiel, C.: Multitemporal scale surface changes of small glacier systems in permafrost environments

P 11.3 Fischer M., Huss M., Hoelzle M.: Use of a new long-range terrestrial LiDAR system to monitor the mass balance of very small glaciers

P 11.4 Molina E., Sikos F., Rados M., Chaparro N., Samata J., Montoya N., Jiménes L., Gonzales G., Torres L., Gómes J., Cruz R., Giraldez C., Drenkhan F., Haeberli W., Huggel C., Schauwecker S.: Initiation Of Mass Balance Monitoring At Glaciar Suyuparina, Cordillera Vilcanota, Peru

P 11.5 Colonia D., Haeberli W., Torres J., Schauwecke S., Cochachin A., Tacsi A., Santiago A.: An Inventory Of Possible Future Lakes In The Cordillera Blanca, Peru

P 11.6 Hoelzle, M., Hauck, C.: Long-term energy balance measurements at three different mountain permafrost sites in the Swiss Alps

P 11.7 Leinss S., Hajnsek I.: Swiss glaciers: TanDEM-X time series vs. SwissAlti3D

P 11.8 Naegeli K., Huss M., Hoelzle, M.: Evaluation of automatic weather station data to observe the characteristics and changes in glacier surface albedo

P 11.9 Salzmann N., Huss M., Machguth H., Sold L., Linsbauer A., Joerg P., Leysinger-Vieli G., Hoelzle M.: 10 years of MB measurements on Findelengletscher, VS, Switzerland

P 11.10 Crivelli Ph., Horender S., Paterna E., Lehning M.: Measuring snow surface topologies and its changes using Microsoft's Kinect

P 11.11 Haberkorn A., Phillips M., Kenner R., Rhyner H., Hoelzle M.: Ground thermal regime and its relation to snow cover in Alpine rock walls

P 11.12 Jörg-Hess S., Griessinger N., Zappa M.: Extended-range probabilistic forecasts of snow water equivalent and runoff in mountainous areas

P 11.13 Marmy A., Rajczak J., Kotlarski S., Salzmann N., Hauck C.: Projections of permafrost evolution in the Swiss Alps coupling climate and soil models

P 11.14 Nendaz T., Lambiel C.: Long term monitoring of the Mont Dolin rock glacier (Swiss Alps)

P 11.15 Staub B., Hasler A., Delaloye R.: Gap filling procedures for ground surface temperature time series of the PERMOS network

P 11.16 Wicki A., Hauck C., Pellet C., Hilbich C., Kemna A., Weigand M., Wege S.: Spatial and temporal variability of soil moisture in permanently frozen ground at Schilthorn (Swiss Alps)

P 11.17 Schneebeli M., Proksch M., Matzl M., Weissbach S.: Antarctic snow stratigraphy - new methods and insights

P 11.18 Proksch M., Gouttevin I., Langer M., Ebner P., Fierz C., Schneebeli M.: Snow microstructure and modelling in support of permafrost science

P 11.19 Wiese M., Schneebeli M.: Imaging of snow algae in natural snow using phase-contrast tomography

P 11.20 Helfricht K., Lehning, M., Sailer R., Kuhn M.: The contribution of locally extreme snow depths to the winter snow cover volume of Alpine glaciers in the Ötztal Alps, Austria

P 11.21 Sold L., Huss M., Hoelzle M.: Towards a better representation of snow accumulation distribution in glacier mass balance models

11.1

Accumulation rates on Abramov Glacier, Kyrgyz Pamir between 2001 and 2013

Martina Barandun[1], Leo Sold[1], Matthias Huss[1,2], Erlan Azisov[3], Nadine Salzmann[1], Ryskul Usubaliev[3], & Martin Hoelzle[1]

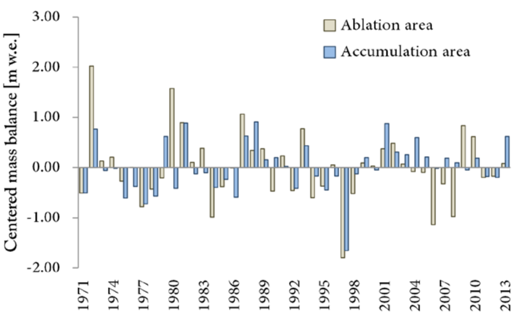
[1] *Department of Geoscience, University of Fribourg, Fribourg, Switzerland (martina.barandun@unifr.ch)*
[2] *Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland*
[3] *Central Asian Institute of Applied Geosciences (CAIAG), Bishkek, Kyrgyzstan*

Glacier mass balance is a good indicator for climate change. In Central Asia melting glacier ice presents a significant contribution to total runoff, and the water supply is highly critical for irrigation in the downstream areas of the major mountain ranges in this region. Data from long-term glacier monitoring programmes provide the scientific basis for climate change analysis and the development of sound models for future projection and impact assessments. Abramov Glacier, an important reference glacier located in the Kyrgyz Pamir, was continuously monitored from 1968 to 1998. With the breakdown of the USSR the scientific program at the majority of monitored glaciers in Central Asia stopped immediately. On Abramov Glacier, mass balance measurements have only been re-established in 2011. To guaranty continuous long-term monitoring, methods have to be developed to close the data gap between 1998 and 2011.

In summer 2013 we applied 800MHz Ground Penetrating Radar (GPR) in the accumulation area of Abramov Glacier to detect annual layers in the upper most firn. The GPR profile of almost 3 km length reaches a depth of almost 18m. A maximum of 13 pronounced internal reflection horizons was observed. The well visible horizons are interpreted as high-density or ice layers that formed at previous summer surfaces. The collected data presents a unique indication on the snow accumulation pattern during the past decade but is sensitive to a potential misinterpretation of reflection horizons in the radar profiles, leading to a shift of the layer chronology. We assume that all detected reflection horizons are previous summer surfaces, but take into account that thin or non-existing layers cannot be resolved by the GPR.

We used the GPR data to calculate annual accumulation rates (Sold et al, 2014) and derived possible maximal elevation changes at point locations on the profile using simple assumptions. The inferred elevation changes were then compared to the results of a distributed mass balance model (Huss et al, 2009) and to surface elevation changes based on digital terrain models from 2000 and 2011 (Gardelle et al. 2013). Whereas the model tends to underestimate the detected change in height based on the GPR data, the geodetic calculations indicate an overestimation.

Further, we calculated the centered mass balance at single point locations in the accumulation and the ablation area, for which GPR data and long-term glaciological measurements since 1968 were available. Trend analyses show an intensified ablation and a simultaneous increase in accumulation at the selected locations over the past 15 years. However, to make more sound statements, additional information such as the dating of an ice core is need.

A


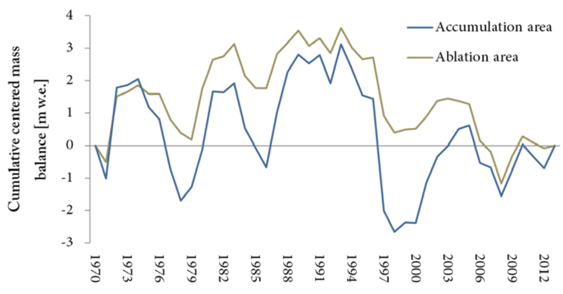
B


Figure 1. Centered (A) and cumulativ centered (B) mass balance for a point location in the accumulation area and for one in the ablation area. From 1971 to 1994 and from 2012 to 2013 glaciological measurements and from 2001 to 2011 GPR data was used. Note that measurement gaps are filled in with the modeled mass balance at the point location.

REFERENCES

Gardelle, J., Berthier, E., Arnaud, Y., & Kääb, A. 2013: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999-2011. The Cryosphere, 7, 1263-1286.

Huss, M., Bauder, A., & Funk, M. 2009: Homogenization of long-term mass-balance time series. Annals of Glaciology, 50(50), 198-206.

Sold, L., Huss, M., Eichler, A., Schwikowski, M., and Hoelzle, M. (Accepted). Recent accumulation rates of an alpine glacier derived from firn cores and repeated helicopter-borne GPR. The Cryosphere Discussions.

11.2

GNSS-based monitoring of kinematic glacier surface deformation at the A.P. Olsen Ice Cap

Geo Boffi[1], Andreas Wieser[1], Daniel Binder[2], Wolfgang Schöner[2]

[1] *Institute of Geodesy and Photogrammetry, ETH Zürich, Stefano-Franscini-Platz 5, 8093 Zürich (geo.boffi@geod.baug.ethz.ch)*
[2] *Climate Research Department, Central Institute for Meteorology and Geodynamics (ZAMG), 1190 Vienna, Austria*

Annual glacial lake outburst floods (GLOF) at the southeast outlet glacier of the A.P. Olsen Ice Cap (northern-east Greenland) represent a hydrological extreme event with major consequences on the glacier motion. The response of the cold glacier to these events is not fully explained by the current understanding of glacier mechanics (Sugiyama et al. 2007). For this reason Spatially and temporally well distributed measurements of surface dynamics and surface deformations are highly valuable source of information for the assessment of this kind of glacial processes because it allows investigating glacier dynamics under rapidly changing stress conditions. This should help to better understand the relation between glacier surface dynamics and glacial hydrology.

A geodetic and geophysical monitoring network has been installed in spring 2012 with the goal of delivering a continuous data set of GPS observations and passive seismic data during the fill- and drain cycle of the ice-dammed lake. The kinematic monitoring is established using a network of low-cost and low power single-frequency GPS stations. All of them are set up for continuous measurements with a sampling rate of 10 s in order to detect sub-daily changes in glacier dynamics as well as changes with longer time scales, e.g. seasonal ones. In order to provide a GPS reference solution for at least one station (i.e. to partially validate the results), an additional station is equipped (since spring 2014) with a double frequency receiver. For obtaining better time resolution of the surface dynamics and stress field changes than with static processing of time windows of a few hours, we process all GPS data kinematically at 0.1 Hz using a Kalman Filter. A coordinate random walk model is employed to represent site motions.

The results obtained so far indicate that a relative accuracy (between GPS stations) of a few centimeters is achievable for the kinematic solutions using differential processing of single-frequency data. The 2012 GPS data show changes of the horizontal flow velocity on the order of 4 mm/h and for a short time (approximately 8 hours) even a reversal of local flow direction at station 2 (fig. 1a) immediately before and during the GLOF. Sugiyama et al. (2007) reported similar dynamic consequences during the outburst of Gornerlake, Switzerland. Besides the observed dynamics during the outburst, the GPS data revealed also a highly dynamic GLOF initiation phase. About one week before the GLOF significant horizontal displacement and uplift of 5 to 10 cm occurred at stations 2-4 (fig. 1b) as compared to the trend of surface motion (accounting for ablation).

Figure 1 Horizontal displacement during the GLOF-period in 2012 (left). Horiziontal and vertical motion anomalies of stations 2, 3 and 4 during initiation phase and outburst of the GLOF.

The results of the GPS processing with their high temporal resolution and accuracy are useful for better understanding of sub- and englacial triggering mechanisms of outburst floods, but so far they required significant manual interaction during data processing to avoid divergence of the processed time series due to undetected errors in the raw data. The dynamic model used within the Kalman Filter needs to be optimized for the slow motion, and additional quality control mechanisms need to be developed in order to automatically detect and avoid divergence of the filter.

REFERENCES

Sugiyama S., A. Bauder, P. Weiss and M. Funk. 2007. Reversal of ice motion during the outburst of a glacier-dammed lake on Gornergletscher, Switzerland. J. Glaciol., 53(181), 172–180.

11.3

Current evolution of small glacier systems in alpine permafrost environments in relation with their internal structure

Jean-Baptiste Bosson & Christophe Lambiel

[1] *Institut des dynamiques de la surface terrestre (IDYST), Université de Lausanne, Bâtiment Géopolis UNIL Mouline, CH-1015 Lausanne (jean-baptiste.bosson@unil.ch)*

Numerous small glacier systems (<0.5 km^2) are present in alpine permafrost environments. In addition to their weak glacial dynamics and polythermal regime, they are commonly characterized in high relief environments by a huge amount of debris and glacier-permafrost interactions. These landforms, where massive glacier ice (covered or not by debris), ice-debris mixture and unconsolidated sediments coexist and sometimes interact, experience contrasted responses in the context of intensifying global change. Despite their important role of alpine water and sediment flux systems and because they are situated at the frontier between glacial and periglacial researches, the characterisation of these systems and of their current evolution in a rapidly changing cryosphere remains a challenging task.

This study explores the current differential evolution within three small glacier systems located in permafrost environments: Tsarmine (Arolla, VS), Entre la Reille (les Diablerets, VD) and les Rognes (St-Gervais, France). The spatial heterogeneity of surface dynamics (annual and seasonal velocities, surface lowering, summer vs. winter dominant dynamics, early summer vs. late summer dominant dynamics, downslope movement vs. surface lowering dominant dynamics) pointed out with 3 years dGPS monitoring correspond to changes in internal structure characteristics (distribution of ground ice, ice/sediment proportion, thickness of debris cover, probable nature and temperature of the ice), illustrated by electrical resistivity tomographies. Any direct measurements have been carried out in the spatially limited bare ice areas of these systems. In sedimentary surface areas, four main zones with specific behaviours can be outlined:

- *Debris covered glacier parts* have important surface dynamic. In addition to ice flowing and sliding, a rapid melt-out occurs. Summer dominant activity typically illustrates the hydrological forcing on glaciers where basal sliding and ice melt are intensified.
- *Low active heavily debris covered glacier parts* have a weaker surface dynamics, dominated by ice melt. Climate signal is attenuated and delayed in consequence of the weak thermal conductivity of the thick debris cover.
- *Marginal ice-debris mixture* (rock glacier, ice-cored moraine) present weak to moderate geomorphic activity. Changes seem to be linked with the downslope slow deformation of frozen sediment body. The several meters thick active layer noticeably attenuated and inverted (winter dominant activity) the climate signal.
- *Debris accumulations without ice* have a null to weak surface activity. The weak detected movements are mainly related to superficial postglacial rebalancing and localised summer mass wasting.

11.4

Onset and development of destabilization phases of rock glaciers in the Swiss Alps.

Luc Braillard[1], Reynald Delaloye[1], Damien Abbet[1], Chloé Barboux[1], Sébastien Morard[1], Benno Staub[1]

[1] *Department of Geosciences/Geography, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg (name.surname@unifr.ch)*

Destabilized rock glaciers are periglacial landforms moving faster than a few meters per year on mountain slopes, exposing sometimes scarps or crevasses features. The current (5-10 years) kinematical behaviour of 8 rock glaciers located in the Swiss Alps has been systematically investigated by performing regularly repeated DGPS surveys. Moreover, information concerning their internal structure has been gained by performing geophysical measurements.

We present here the results of a study that focuses on the onset and on the development of these destabilization phases. Based essentially on the analyse of former aerial and terrestrial photos going back to 1930, this contribution aims to provide results and discussion elements on the triggering and controlling factors of the destabilization phase(s).

Our study points out the large diversity of occurrence, development and kinematical behaviour of the destabilization phases on the investigated rock glaciers. One documented destabilization phase occurred for instance already around 1940 (Grabengufer), another one probably started already before (Dirru), another one in 1958 (Gugla/Laengenschnee), another one only during the last ten years (Gugla/Bielzug), etc. Destabilization phases can be short (a few years) and intense (velocity up to 100 m/year or even more), but also continuing for several tens of years. They can concern a part of or the entire rock glacier, reactivating former inactive – but still frozen – terminal sections.

The involved triggering mechanisms can be diverse. Beside the role played by the internal structure of the rock glacier, destabilization phases can be the result of the combined influence of several factors such as: thermal state of the permafrost, topography of the stable bedrock on top of which the rock glacier is moving, modification of the geometry of the rock glacier, or local overloading in debris (consecutive to the Little Ice Age advance of a glacier, to a landslide or to increased rock fall activity from headwalls). In the two latter situations a mechanical surge is triggered, which can take up to decades to reach the rock glacier front. The progression of the rock glacier front over a steep topography can in turn pull down a large part (if not the whole) of the rock glacier behind it.

11.5

Quantification and mapping of snow surface dynamics with terrestrial radar interferometry: From avalanche mapping to snow creep measurements

Rafael Caduff[1], Andreas Wiesmann[1], Yves Bühler[2]

[1] *GAMMA Remote Sensing AG, Worbstrasse 225, CH-3073 Gümligen, Switzerland (caduff@gamma-rs.ch)*
[2] *WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos, Switzerland*

Information about snow dynamics is important for snow avalanche hazard assessment and mitigation measure planning in alpine areas. An important piece of information is the accurate mapping of avalanche extents and the identification of the release time regardless of weather conditions in particular for road and railway safety. Coherent observations with Ku-Band terrestrial radar interferometry at sampling intervals below the decorrelation time for snow surfaces (minutes to few hours) can be used to map disturbances of the snow surfaces. Changes in snow properties e.g. snow metamorphosis and melting as well as mechanical disturbances (e.g. freerider-tracks, wind drift, avalanches) change the scattering behavior (magnitude and phase of the backscattered echo) of the radar resolution cell from one radar image to another. Those changes can be expressed with the interferometric coherence. Coherence maps finally are used to locate changes induced by avalanche events in the spatial and the temporal domain. The resolution of the radar imagery allows even the detection of very small events (few tens of meters).

We present recent results from Winter 2013/2014. A first campaign includes the short term monitoring with the GAMMA Portable Radar Interferometer (GPRI, Figure 1) during two avalanche blasting experiments performed on 31 January 2014 at Flüelapass, Davos, GR. The results revealed the feasibility of accurate avalanche extent mapping even during strong changing weather conditions (Figure 1a). Additionally, high-frequency radar sampling at a fixed look angle during an avalanche release led to insights in the velocity profile of an avalanche. A preliminary assessment of the frontal velocity revealed maximum values of 71 km/h (Figure 1b). Independent validation of the measured values however is still ongoing. A second, continuous campaign started on 31 January 2014 and ended on 24 April 2014. The test site was the Dorfberg slope in Davos, GR. Results include the detection and mapping of a few smaller snow-glide events using interferometric coherence maps. The temporal resolution of the detection of such an event is given by the observation rate of the system and the on-site data processing time. A sampling rate of one scene per minute could be applied.

The experiment setup allowed as well temporal sampling faster than the decorrelation time of snow which led to the interpretation of the differential phase. Continued phase shifts in the area were detected resulting from snow surface deformation (snow creep/glide). Using the interferometric phase, maps of continuous mechanic snow surface deformation in line of sight can be created, showing the slope-wide snow creep activity. Such areas could be validated with webcam imagery showing extension ruptures and bulging of creeping snow (Figure 1c). A maximum line of sight surface displacement per day of 2.3 m was detected during the campaign. Additionally, a deformation history prior to a small snow glide event could be measured which showed an acceleration of the displacement velocity prior to the release of the snowpack (Figure 1d).

In our presentation we will give a short introduction into the measurement principle of terrestrial radar interferometry regarding snow observations and state necessary preconditions and limitations for the different modes presented followed by an introduction of the measurement setup at the different test-sites,. The main focus will be on the results and a critical discussion thereof. Finally, an outlook on future validation will be given and potential fields of application will be discussed.

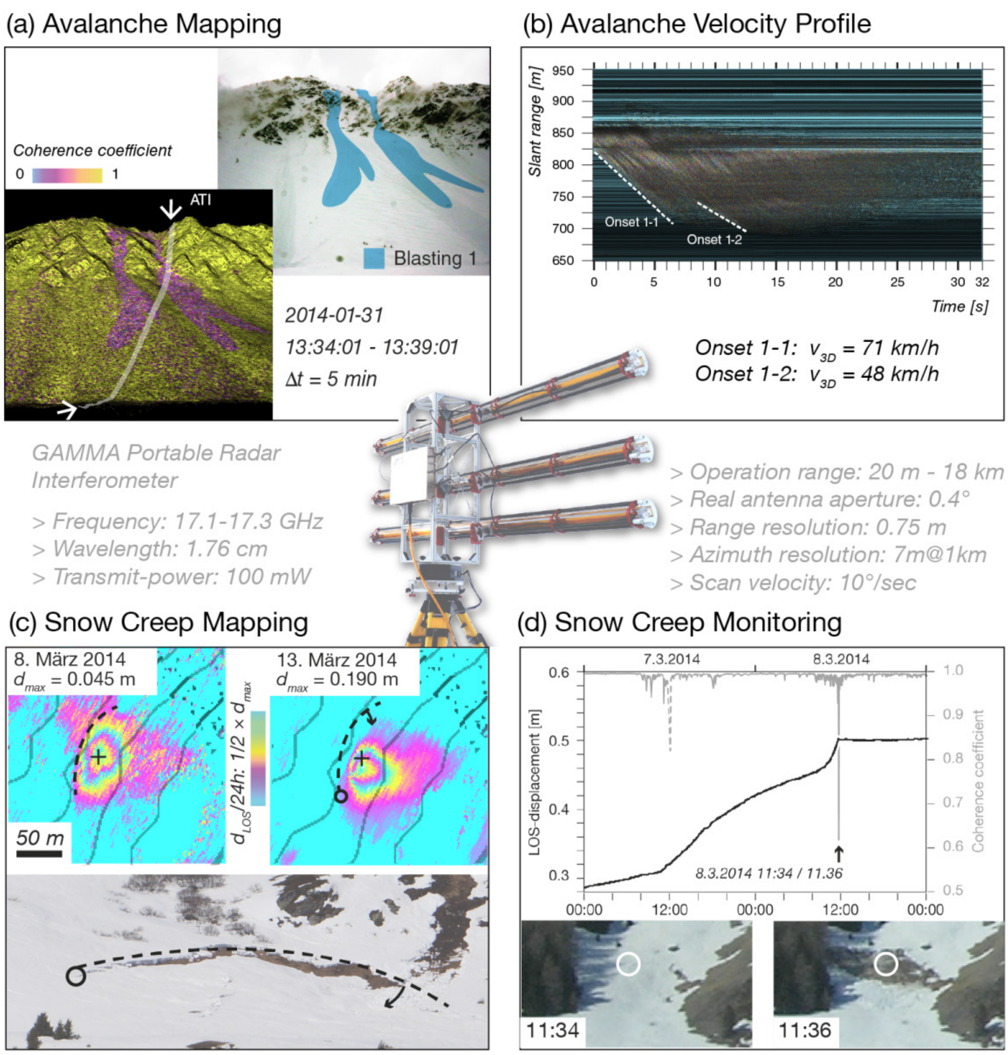


Figure 1. Results from the GPRI campaigns 2014. (a) Avalanche map after an artificial release at Flüelapass, Davos, GR, validated with photography. (b) Temporal profile of an avalanche and corresponding measured frontal velocities. Location of profile line indicated as ATI-Line in (a). (c) Details of an area with measured snow creep. Scale is normalized. The photo shows that the entire snow pack is affected by the deformation. (d) Detail of the temporal evolution of the surface displacement prior to a small snow slab breakoff.

11.6

Propagation characteristics of acoustic waves in snow under laboratory conditions

Achille Capelli[1], Jagdish Chandra Kapil[2], Ingrid Reiweger[1], Alec van Herwijnen[1], Jürg Schweizer [1] & Dani Or[3]

[1] *WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf (achille.capelli@slf.ch)*
[2] *Snow and Avalanche Study Establishment SASE, Chandigarh (UT)-160036, India*
[3] *Department of Environmental Sciences, ETH Zurich, Universitätsstrasse 16, CH-8092 Zurich*

Acoustic emission (AE) analysis is a promising technique for monitoring snow slope stability with potential application in early warning systems for avalanches. Current research efforts focuses on identification and localization of acoustic emission features preceding snow failure and avalanches. However, our knowledge of sound propagation characteristics in snow, including velocity and attenuation, is still limited. While some characteristics have been determined for the frequency range below 10 kHz, recent snow failure experiments suggest that the peak frequency is in the ultrasound range between 30 kHz to 500 kHz.

We therefore studied the propagation of pencil lead fracture (PLF) signals through snow in the ultrasound frequency range by performing laboratory experiments with columns of artificially produced snow of varying density and temperature. The attenuation constant was obtained by varying the size of the columns to eliminate possible influences of the snow-sensor coupling. The attenuation constant was measured for the entire PLF burst signal and for single frequency components.

In addition, propagation velocities were calculated from the arrival times of the acoustic signals. While longitudinal wave velocities could be determined successfully, the results obtained from transversal waves were ambiguous and may need further investigation. Their successful detection would allow determining the elastic properties of snow (elastic moduli and Poisson’s ratio) from the p- and s-wave velocity. This would be highly relevant, as the elastic properties of snow are not well known.

11.7

Flow and Temperature Dynamics in the Hydrologic Response of Alpine Catchments: Travel Time Formulation and Geomorphologic Signatures

Francesco Comola[1], Bettina Schaefli[2], Andrea Rinaldo[2, 3], Michael Lehning[1, 4]

[1] *Laboratory of Cryospheric Science, School of Architecture, Civil and Environmental Engineering , Ecole Polytechnique Fèdèrale de Lausanne, Route Cantonale, CH-1015 Lausanne (francesco.comola@epfl.ch)*
[2] *Laboratory of Ecohydrology, School of Architecture, Civil and Environmental Engineering , Ecole Polytechnique Fèdèrale de Lausanne, Route Cantonale, CH-1015 Lausanne*
[3] *Dipartimento di Ingegneria Civile, Edile e Ambientale Università di Padova, via Loredan 20, I-35131 Padovay*
[4] *WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260, Davos Dorf*

We present a travel time formulation of water and energy transport at sub-catchment scale. The derived equations are implemented in Alpine3D, a physically-based model of snow processes, which provides the necessary boundary conditions to perform hydro-thermal response simulations of Alpine catchments. The model set-up accounts for advective and non-advective energy fluxes to perform spatially distributed simulations of streamflow and temperature in river networks having an arbitrary degree of geomorphological complexity. The model gives reliable predictions of streamflow and temperature, as shown by comparing modeled and measured hydrographs and thermographs at the outlet of the Dischma catchment (45 km^2) in the Swiss Alps. Our model setup is applied to investigate the role of hillslope aspects, representing the main control on radiation and snowmelt patterns, in the flow regime of the study catchment. The distributed simulation results show that snowmelt-induced discharge exhibits a visible geomorphologic signature of aspects at sub-catchment scale, but this progressively fades out going from headwater streams to the outlet. Accordingly, the geomorphologic signature is scale-dependent: it is significant at small scales where the high aspect correlation generates predominant orientations but is lost at larger scales where aspects are de-correlated and different orientations are averaged out. We further apply the model to investigate the geomorphologic signature of drainage density in the thermal regime of the study catchment. The results show that the contribution of the advective energy fluxes becomes progressively smaller when the drainage density increases, while the one of the non-advective energy fluxes becomes larger. Moreover, such variations balance out at the catchment outlet, where the temperature signal is not sensitive to the increasing drainage density. The relevance of the performed invetigations stems from the increasing scientific interest concerning the impacts of the warming climate on water resources management and temperature-influenced ecological processes.

11.8

The impact of Saharan dust events on long-term glacier mass balance in the Alps

Jeannette Gabbi[1], Matthias Huss[1], Andreas Bauder[1] & Margit Schwikowski[2]

[1] *Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Wolfgang-Pauli-Strasse 27, CH-8093 Zurich (gabbij@vaw.baug.ethz.ch)*
[2] *Paul Scherrer Institute (PSI), CH-5232 Villigen PSI*

Saharan dust falls are frequently observed in the Alpine region and are easily recognized by the unique yellowish coloration of the snow surface. Such Saharan dust events contribute to a large part to the total mineral dust deposited in snow and impact the surface energy budget by reducing the snow and ice albedo. In this study we investigate the long-term effect of such Saharan dust events on the surface albedo and the glacier's mass balance.

The analysis is performed over the period 1914-2013 for two field sites on Claridenfirn, Swiss Alps, where an outstanding 100-year record of seasonal mass balance measurements is available. Based on the detailed knowledge about the mass balance, annual melt and accumulation rates are derived. A firn/ice core drilled at the glacier saddle of Colle Gnifetti (Swiss Alps) provides information on the impurity concentration in precipitation over the last century.

A mass balance model combined with a parameterization for snow and ice albedo based on the specific surface area of snow and the snow impurity concentration is employed to assess the dust-albedo feedback. In order to track the position and thickness of snow layers a snow density model is implemented. Atmospheric dust enters the system of snow layers by precipitation and remains in the corresponding layer as long as there is no melt. When melt occurs, the water-insoluble part of the dust of the melted snow is supposed to accumulate in the top surface layer.

The upper site has experienced only positive net mass balance and dust layers are continuously buried so that the impact of strong Saharan dust events is mainly restricted to the corresponding year. In the case of the lower site, the surface albedo is more strongly influenced by dust events of previous years due to periods with negative mass balances. Model results suggest that the enhanced melting in the 1940s yield even higher dust concentrations in 1947 compared to years with exceptional high Saharan dust deposition due to the accumulation of dust at the surface as the corresponding site migrates from accumulation to ablation area.

11.9
Ten new long-term glaciological mass balance series for Swiss glaciers

Matthias Huss[1,2], Laurie Dhulst[1] & Andreas Bauder[1]

[1] Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Wolfgang-Pauli-Strasse 27, CH-8093 Zurich, Switzerland
[2] Department of Geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg, Switzerland

Mountain glaciers are highly sensitive to changes in climate forcing and their surface mass balance is a valuable indicator of climate change. Globally coordinated monitoring efforts have contributed to a comprehensive set of time series documenting variations in glacier-wide mass balance for about a hundred glaciers. However, only few time series are longer than twenty years and even less start before the 1980s (Zemp et al., 2009). Glaciers in the European Alps are most densely covered with mass balance records. However, given the strong differences in the response of individual glaciers as well as the partly poor representativeness of some series for their respective region, even in the Alps more direct information on mass balance variability is required. Furthermore, only a small fraction of the records yields seasonal mass budget components which are of eminent importance for understanding glacier response to shifts in climatic forcing throughout the 20th century.

In this study, we present ten new long-term series of glacier-wide seasonal mass balance for glaciers in the Swiss Alps mostly starting in the 1950s and continued until today. Additionally, our data set includes several shorter series partly reaching back to the 1920s. Previously unpublished or unevaluated measurements of winter and summer balance form the base of these records. Data was compiled from old archives and from various sources. Most of the in-situ measurements were not intended as full monitoring programs which might explain that these highly valuable data sets were not consistently evaluated so far and were thus unavailable to the scientific community.

Using a new technique employing modelling for spatial extrapolation and homogenization of the seasonal point measurements we infer continuous series of area-averaged mass balance (Huss et al., 2009). The results are validated against independent decadal ice volume changes from photogrammetric surveys (Bauder et al., 2007). Five of the new seasonal mass balance series cover more than 50 years and add a substantial amount of information on the dynamics of regional glacier mass change (Fig. 1). This will strengthen the worldwide data collection on glacier monitoring, especially during the data-sparse period before the 1980s. We compare our results to existing long-term series and present an updated assessment of mass balance variability and sensitivity throughout the European Alps in connection with external drivers.

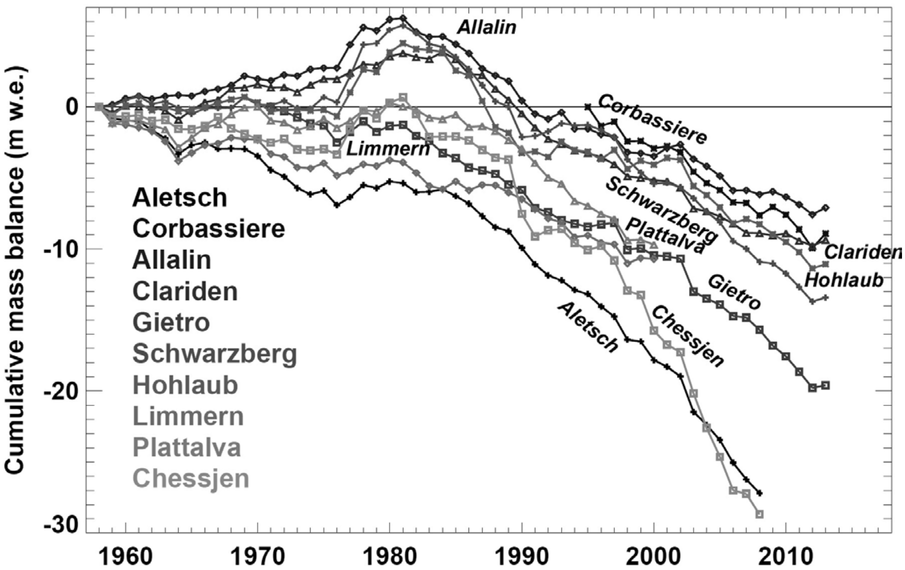


Figure 1. Cumulative glaciological mass balance series for ten Swiss glaciers since 1958.

REFERENCES

Bauder, A., Funk, M., & Huss, M. 2007: Ice-volume changes of selected glaciers in the Swiss Alps since the end of the 19th century, Annals of Glaciology, 46(1), 145-149.

Huss, M., Bauder, A., & Funk, M. 2009: Homogenization of long-term mass-balance time series, Annals of Glaciology, 50(50), 198-206.

Zemp, M., Hoelzle, M., & Haeberli, W. 2009: Six decades of glacier mass-balance observations: a review of the worldwide monitoring network, Annals of Glaciology, 50(50), 101-111.

11.10

Deriving long-term firn stratigraphy from optical borehole camera measurements on Austfonna, Svalbard

Lisbeth Langhammer[1,2] Thorben Dunse[1], Kirsty Langley[1], Elisabeth Isaksson[3] & Jon Ove Hagen[1]

[1] *Department of Geosciences, University of Oslo, Sem Sælands vei 1, NO-0371 Oslo*
[2] *Institute of Geophysics, ETH Zürich, Sonneggstrasse 5, CH - 8092 Zürich (lisbeth.langhammer@erdw.ethz.ch)*
[3] *Norwegian Polar Institue, Fram Cente, NO-9269 Tromsø*

The density of snow and firn is crucial for estimating the mass balance of ice masses by GPR, as well as airborne and spaceborne radar altimeter systems. To determine internal reflection horizons in the firn, independent ground-truth observations are required.

We present a borehole video camera system that provides a proxy of the firn structure in wet-snow zone conditions. A Junior Ultra Low Light borehole video camera and four shallow firn cores were used to investigate the firn stratigraphy close to the Summit camp on the Austfonna Ice Cap, Svalbard. Four videos from residual firn core boreholes and one ice auger borehole are analyzed to simulate an intensity-derived firn stratigraphy record.The firn cores themselves provided ground truth data. The camera lens measures the intensity of light, which is emitted from LEDs and reflected from the borehole wall. To extract a continuous intensity record from the video a Borehole camera video analysis tool was developed. Averaged grayscale values from a predefined section of the borehole wall or an attached mirror underneath the lens were correlated to the position of the camera in the borehole. Depending on a unique threshold value for each video log, the intensity signal was classified as firn or ice sections and compared to the firn cores from the same location. High to moderate agreement (91-63%) between the ground truth data and the intensity-derived stratigraphy is achieved. Two out of four intensity records show approximately the same amount of ice as was present in the corresponding firn core. In general, thin ice layers are underrepresented, whereas thicker ice agglomerations are more likely to be detected with the borehole camera. The quality of the intensity records is highly influenced by the technical set-up and operation of the camera system in cold climate environments. Further improvement of the set-up is recommended to achieve the same quality as ground truth firn core records.

The described borehole camera system is a logistically inexpensive tool to observe the stratigraphy of firn in regions with substantial refreezing of meltwater below the surface. Ice structure, firn stratigraphy and densification surveys as well as in situ or spaceborne remote sensing measurements of the mass balance benefit from the implementation of the borehole camera system in the field.

11.11

Mixed-mode shear-compression failure criterion for weak snowpack layers

Ingrid Reiweger, Johan Gaume, Jürg Schweizer

WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf (reiweger@slf.ch)

Snow slab avalanches begin with a failure in a weak snow layer beneath a cohesive slab followed by crack propagation within the weak layer. The nature of the initial failure within the weak layer is unknown – but debated. Different avalanche release models assume contradictory failure criteria as input parameters. We analysed laboratory experiments on snow failure with samples containing a weak snow layer of either depth hoar or buried surface hoar. These layers are the most relevant ones for avalanche release. The failure behavior of these layers – the most relevant for avalanche release – can well be described with a modified Mohr-Coulomb model. Therefore, we propose a mixed-mode failure criterion to be used in avalanche release models.

11.12

Variability of snow thickness changes in steep rock faces based on terrestrial laser scanning

Christian Sommer[1,2], Rebecca Mott[1], Michael Lehning[1] & Sophia Haussener[2]

[1] *WSL-Institut für Schnee- und Lawinenforschung SLF, Flüelastrasse 11, CH-7260 Davos Dorf (sommer@slf.ch)*
[2] *Section de génie mécanique, EPFL, CH-1015 Lausane*

During this Master's thesis, Terrestrial Laser Scanning (TLS) was used to measure snow thickness changes (perpendicular to the surface) in rock faces. The goal was to identify which processes and parameters are important for the variability of snow accumulation and ablation. The knowledge of the spatial variability of the snow cover is important for hydrology, ecology, climatology and avalanche forecasting. Two different rock faces in the region of Davos in eastern Switzerland were scanned before and after snowfall events, each with a different laser scanner. An elaborate postprocessing procedure was necessary to produce useful results. The snow thickness changes were analysed qualitatively and quantitatively using simple statistics and linear correlation coefficients. Furthermore, the applicability and precision of TLS was studied.

It was concluded that given an appropriate postprocessing, TLS is a viable experimental method. Most important is a precise registration, which usually necessitates Multi Station Adjustment (MSA). The snow thickness changes could then be measured with a precision of several centimetres.

It could be shown that snow is mostly deposited in the flatter and smoother areas of a rock face. Very steep terrain (up to 70°) could however still accumulate and retain a considerable amount of snow. Extremely steep (up to 85°) and rough areas can only temporarily hold a small amount of snow. Wind and avalanches appear to be the dominant processes responsible for the snow distribution. For snowfall events with only weak wind, the snow thickness changes correlate with topographic parameters such as slope angle and roughness, but the correlation is always quite weak.

REFERENCES

Deems, J., Painter, T. & Finnegan, D. 2013: Lidar measurement of snow depth: a review. Journal of Glaciology 59.215, 467–479.

Wirz, V., Schirmer, M., Gruber, S. & Lehning, M. 2011: Spatio-temporal measurements and analysis of snow depth in a rock face. The Cryosphere 5.4, 893–905.

11.13

Sensitivity of operational snow melt predictions to different modelling setups

Mirjam Stawicki[1], Jan Magnusson [2] & Tobias Jonas [2]

[1] Geographisches Institut, University of Bern, Hallerstrasse 12, CH-3012 Bern (mirjam.stawicki@unibe.ch)
[2] WSL-Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf

In Switzerland, snow is an essential component of the hydrological cycle. About one third of the total annual precipitation falls as snow and it is estimated that as much as 42% of the total runoff origins from snowmelt.

The operational snow hydrological service (OSHD) run by the WSL-Institute for snow and avalanche research SLF monitors the spatio-temporal distribution of snow water resources in Switzerland. The OSHD provides periodic snowmelt forecasts which contribute to the Swiss federal warning framework for natural hazards. These forecasts are based on snow model simulations that incorporate observational data from several monitoring networks using advanced data assimilation techniques.

In this study the current OSHD snow model framework was evaluated for 132 strong snow melt events that occurred over the last 15 years. A special model testbed allowed assessing the impact of data assimilation and the sensitivity to different model input scenarios. We demonstrate that assimilation of snow monitoring data affects snowmelt predictions in two different ways. Moreover we highlight systematic discrepancies between model results when driven by observational data versus data from the numerical weather prediction system COSMO.

11.14

Fast ice flow, troughs, overdeepenings and subglacial hydrology

Mauro A Werder[1]

[1] Geographisches Institute, Universität Zürich

This presentation explores the role of subglacial hydrology in fast flowing topographically constrained outlet glaciers. Subglacial water flow is strongly influenced by the bed topography through the dependence of the melting point of ice on pressure. Thi means that water descending into a trough or an overdeepening has more energy available to melt channels and conversely water ascending out has less or even no energy available for melt. The latter process leads to a reduced drainage capacity and, consequently, to increased water pressures.

Therefore these processes lead to increased water pressures in subglacial troughs, in particular with overdeepened sections. I will discuss the implications for the formation of troughs and overdeepenings.

P 11.1

Ice flow in the Alps during the last glacial maximum, a modeling approach

Patrick Becker

Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich, Wolfgang-Pauli-Str. 27, CH-8093 Zürich (becker@vaw.baug.ethz.ch)

About 30,000 years before present at the end of the Würm Ice Age, glaciers reached the maximum extent and most of the Alpine mountain environment and wide parts of the Alpine forelands were covered by ice. The impact of the last glacial maximum (LGM) to the surrounding environment offers a good opportunity to study the predominating extent of glaciation as well as the predominating climate in an indirectly manner.

Latest studies by the group of C. Schlüchter assembled evidences found in the field to reconstruct a map of the glacier extent at LGM. The map shows the situation at the Rhone valley: Ice was flowing from the main accumulation area, the Rhone ice dome, situated close to todays location of the Rhone glacier, through the Rhone valley towards the Lake Geneva. Behind the lake the ice diffluenced by the barrier of the Jura to northeast and southwest. Furthermore the study discussed erratic boulders that have been found in the Alpine foreland which origin was assigned to the Saas valley, Upper Valais. This long transport trajectory indicate the extent of the glacier. It is not completely clear if they were transported within one Ice Age (single glacier advance) all the long way down to the forelands or whether they were transported by multiple glacier advances.

Further uncertainties are caused by evidences found at the Simplonpass area. E. g. striations have been identified at the Staldhorn indicating an ice flow from north to south. This would indicate a transfluence of ice of the Rhone glacier out of the Rhone valley over the Simplonpass into the drainage system of the Po river.

The reason for this transfluence is still not well understood. At the time of LGM one can assume a feed of the glaciation in the Rhone valley by the inflow of glaciers originating at the Matter valley, Saas valley and the Aletsch region. One reason for the transfluence could be caused by the glacier outflow coming from the Visp valley (drained by ice masses from Matter and Saas valley):

One can hypothesize a barrier of the Rhone valley built by ice masses coming from the Visp valley. Hence, the ice of Rhone glacier could have been dammed and forced to south over the Simplonpass.

The problem will be studied with the aid of a numerical simulation. The flow of glaciers is governed by the Stokes Equations. Numerically solving them is computationally expensive for large glaciers. For this reason we use the Parallel Ice Sheet Model (PISM), a free software implementation of a hybrid scheme that combines the Shallow Ice Approximation (SIA) and the Shallow Shelf Approximation (SSA). PISM uses the SSA as a „sliding law“ for grounded ice which is already modeled everywhere by the non-sliding SIA.

In a first step the retreat of Grosser Aletschgletscher in the last 100 years will be studied. During this period the glacier surface topography as well as the climate forcing that is given by the mass balance is well-known. Results will be validated against observations from measurements.

Further large scale computations or the Upper Valais at the time of the LGM will be carried out to get insights into the glacier drainage system. Simulating the Upper Valais area should clarify the question of a possible North-South-Transfluence over the Simplonpass into the Piedmont region, Italy.

P 11.2

Multitemporal scale surface changes of small glacier systems in permafrost environments

Maxime Capt[1], Jean-Baptiste Bosson[1], Natan Micheletti[1] & Christophe Lambiel[1]

[1] *Institut des dynamiques de la surface terrestre (IDYST), Université de Lausanne, Bâtiment Géopolis UNIL Mouline, CH-1015 Lausanne (maxime.capt@unil.ch)*

Since the end of the Little Ice Age, glaciers have experienced intense mass loss in response to global change. In the Alps, this shrinking has not been uniform over the twenty-first century: some periods have been favorable to glaciers stabilization, or even their advance. Moreover, the burying of some glaciers under a several centimeters thick debris cover significantly reduces the ice melt and stabilize the glacier front. The research on debris-covered glaciers has increased in last decades but numerous questions remain open, especially in permafrost environments where clean ice, debris-covered ice, frozen and unfrozen sediments accumulations may complexly coexist.

This study examines the dynamics of two small glaciers in the permafrost environments of western Switzerland: Tsarmine (Arolla, Valais) and Entre la Reille (Diablerets, Vaud). These small glacier systems (<0.5 km^2) are characterized by extended debris-covered ice, huge moraine constructions and marginal rock glacier morphology. Through the manipulation of DTMs and orthophotos, this study highlights the spatial differences in the surface dynamics within these systems, at several time scales (decadal, annual and seasonal).

The displacement vectors as well as the loss/gain volumes maps show that there is a relationship with climate in these areas, and that the dynamics change significantly between the different zones in relation to their specificities (ice composition, nature of the ice, debris cover extension and thickness). At Tsarmine for example, the debris-covered glacier surface motion can exceed 3m/year while the values are lower than 60cm/year on the marginal rock glacier. At seasonnal scale, LiDAR (light detection and ranging) scans comparison point out the importance of hydrological forcing (especially related to snow and ice melt) on surface dynamics : the ice melt and the surface motion are accelerated.

REFERENCES

Goudie, A.S. (2004). Encyclopedia of geomorphology – Volume 2. Londres: Goudie, A.S.

Otto et al. (2009). Quantifying sediment storage in a high alpine valley (Turtmanntal, Switzerland). Earth surface processes and landforms, 34, 1726-1742.

Vaughan et al. (2013). 5th Assessment Report of the IPCC. Cambridge University Press: 317-382.

P 11.3

Use of a new long-range terrestrial LiDAR system to monitor the mass balance of very small glaciers

Fischer Mauro[1], Huss Matthias[1,2] & Martin Hoelzle[1]

[1] *Department of Geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg, Switzerland (mauro.fischer@unifr.ch)*
[2] *Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, CH-8093 Zurich, Switzerland*

More than 80% of all Swiss glaciers are smaller than 0.5 km^2 and hence belong to the size class of very small glaciers (Fischer et al. 2014a), occuring mostly in cirques, niches and below headwalls where topoclimatical factors and snow accumulation patterns are favourable for the persistence of snow and ice. Very small glaciers have, however, hardly been studied and empirical field measurements are sparse.

Since 2012, both seasonal and annual mass balance of seven very small glaciers in Switzerland is measured using the glaciological method (snow soundings and density measurements at the end of the accumulation season, measuring melt at ablation stakes at the end of the ablation period). Monitoring glacier mass balance is important as it directly reflects the climatic forcing on the glacier. Mass balance can also be reconstructed by means of the geodetic method, which is based on the comparison of two different Digital Elevation Models (DEMs) (e.g. Fischer et al. 2014b). So far, the accuracy of such DEMs mostly derived from airborne or terrestrial laserscanning, photogrammetry or topographic maps limited the time resolution of reliable mass balance measurements resulting from the geodetic method to a multi-annual or decadal scale (Cox and March 2004, Huss et al. 2009). Most recently, the creation of highly accurate DEMs of snowy and icy terrain using a new generation of long-range terrestrial LiDAR (Light Detection And Ranging) devices became possible. This is highly promising for future accurate determination of annual and even seasonal mass balance of small Alpine glaciers (e.g. Grünewald et al. 2010). It may have the potential to circumvent laborious and time consuming glaciological mass balance measurements. Furthermore and because ice flow is reduced for very small glaciers, it may help to improve our understanding of the spatial and temporal component of accumulation and melt processes on Alpine glaciers.

Here we present first results of the comparison of seasonal and annual ice volume changes determined with the new *Riegl* VZ®-6000 long-range LiDAR device with in-situ glaciological seasonal and annual mass balance surveys performed on five very small glaciers in Switzerland (Glacier de Prapio (VD), Glacier du Sex Rouge (VD), St. Anna- and Schwarzbachfirn (UR), and Pizolgletscher (SG)) over the hydrological year 2013/14.

REFERENCES

Cox, L. H., & March, R. S. 2004: Comparison of geodetic and glaciological mass-balance techniques, Gulkana Glacier, Alaska, U.S.A. Journal of Glaciology, 50, 363-370.

Fischer, M., Huss, M., Barboux, C., & Hoelzle, M. 2014a: The new Swiss Glacier Inventory SGI2010: Relevance of using high-resolution source data in areas dominated by very small glaciers. Arctic, Antarctic, and Alpine Research, in press.

Fischer, M., Huss, M., & Hoelzle, M. 2014b: Surface elevation and mass changes of all Swiss glaciers 1980-2010. The Cryosphere Discussions, 8, 4581–4617.

Grünewald, T., Schirmer, M., Mott, R., & Lehning, M. 2010: Spatial and temporal variability of snow depth and ablation rates in a small mountain catchment. The Cryosphere, 4, 215-225.

Huss, M., Bauder, A., & Funk, M. 2009. Homogenization of long-term mass-balance time series. Annals of Glaciology, 50, 198-206.

P 11.4

INITIATION OF MASS BALANCE MONITORING AT GLACIAR SUYUPARINA, CORDILLERA VILCANOTA, PERU

Edwin Molina[1], Felipe Sikos[1], Maxwell Rados[1], Nicacio Chaparro[1], Jaime Samata[1], Nilton Montoya[1], Luís Jiménes[1], Gilbert Gonzales[2], Lucas Torres[2], Jesús Gómes[2], Rolando Cruz[2], Claudia Giraldez[3], Fabian Drenkhan[3], Wilfried Haeberli[3], Christian Huggel[3], Simone Schauwecker[3]

[1] *Universidad Nacional de San Antonia Abad del Cusco, Vicerectorado de Investigción, Facultad de Ingeniería Geológica y Geografía, Departemento Académico de Geografía (emporcel@hotmail.com)*
[2] *Unidad de Glaciologia y Recursos Hidricos, Autoridad Nacional del Agua, Huaraz, Perú*
[3] *Geography Department, University of Zurich, Zurich, Switzerland*

The Cordillera Vilcanota is at the origin of the Rio Vilcanota-Urubamba, containing about 25% of all glaciers in Peru and constuting an important national and regional water resource. In recent decades, glacier shrinkage appears to have been accelerating. Between1988 and 2010, glacier area was reduced at an annual rate of about 4 km^2 from some 360 km^2 to some 270 km^2 (-25%; Hanshaw and Bookhagen 2014) and a total volume loss of 40-45% (from 17-20 km^3 to 9.2-12.4 km^3) can be estimated for the time period 1962-2006 (Salzmann et al. 2013); most of this volume loss seems to have opccurred since the 1980s. Glacier mass balance values had so far not been available but are now initiated at Glaciar Suyuparina with a 3-year program. On a long term, the observations should become part of the national and international glacier monitoring network (cf. WGMS 2013). The project is also part of a major effort – through a combination of projects – to develop hydrological models for the mountain chain in view of policy-oriented climate impact assessments at local to regional scales.

Glaciar Suyuparina is a rather steep south-west oriented mountain glacier (Figure 1) some 15 km north of the Quelccaya Ice Cap, with a surface area of a few km^2 and reaching from a maximum altitude of 5469 m asl down to about 5150 m asl. With an elevation range of some 300 m and a mid-range elevation at 5300 m, the equilibrium line altitude (ELA) with a characteristic accumulation area ratio for zero mass balance on tropical glaciers of about 80% is expected to be near 5200 m asl. Glacier-wide mass balance is determined using the direct glaciological method (stakes and pits) for process understanding and high resolution in time combined with DEM differencing for overall volume/mass changes and calibration of the mesurements. A first high-resolution DEM from airborne LIDAR measurements is available for May 2013. The first year of field observations indicates large local variability of ablation values due to a pronounced microtopography with near-vertical ice cliffs oriented towards the sun and probably having a predominant effect on total ablation (Figure 1). As expected, ablation gradients are extreme (1 – 2 m per year and 100m elevation).

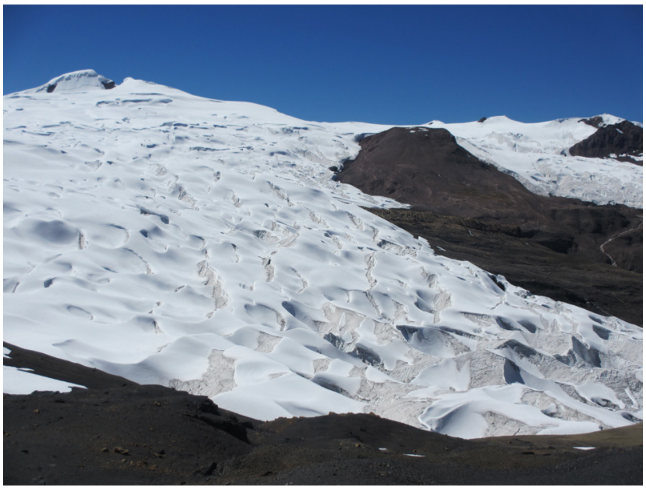


Figure 1. Glaciar Suyuparina in the Cordillera Vilcanota. Note the marked microtopography and its effects on ablation patterns. Photograph W. Haeberli July 2014.

REFERENCES

Hanshaw, M.N. & Bookhagen, B. 2014: Glacial areas, lake areas, and snow lines from 1975 to 2012: status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru. The Cryosphere 8, 359-376.

Salzmann, N., Huggel, C., Rohrer, M., Silverio, W., Mark, B.G., Burns, P.& Portocarrero, C. 2013: Glacier changes and climate trends derived from multiple sources in the data scarce Cordillera Vilcanota region, southern Peruvian Andes. The Cryosphere 7, 102-118. The Cryosphere, 7, 103–118,

WGMS 2013: Glacier Mass Balance Bulletin No. 12 (2010-2011). Zemp, M., Nussbaumer, S.U., Naegeli, K., Gärtner-Roer, I., Paul, F., Hoelzle, M. and Haeberli, W. (eds.), ICSU (WDS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 106 pp., publication based on database version: doi: 10.5904/wgms-fog-2013-11.

P 11.5

AN INVENTORY OF POSSIBLE FUTURE LAKES IN THE CORDILLERA BLANCA, PERU

Daniel Colonia[1], Wilfried Haeberli[2], Judith Torres[1], Simone Schauwecker[2], Alejo Cochachin[1], Arnaldo Tacsi[1] & Alexzander Santiago[1]

[1] *Unidad de Glaciologia y Recursos Hidricos (UGRH), Autoridad Nacional del Agua (ANA), Huaraz, Perú (dcolonia@ana.gob.pe; dfco18@hotmail.com)*
[2] *Geography Department, University of Zurich, Zurich, Switzerland*

Climate change causes dramatic mass losses of glaciers in the Cordillera Blanca. Between the 1970 and 2003 inventories, 27% of the glacier area disappeared (UGRH 2010) and until 2003, a total of 830 new lakes had formed in deglaciating terrain. The identification of possible future lakes is important to understand changes in freshwater storage in the corresponding source areas and to plan for preventive measures concerning possible lake outbursts. A major number of catastrophic events had indeed happened in the Cordillera Blanca (cf. Carey et al. 2012) such as, for instance, the disastrous „aluvión" from the outburst of Laguna Palcacocha on 13 December 1941, destroying the centre of Huaraz and killing several thousand people. As most of the new lakes form in immediate neigbourhood of steep hanging glaciers and high-altitude permafrost rock walls, the probability of severe floods/debris flows from impact waves caused by large rock/ice-avalanches or large moraine landslides is increasing with continued atmospheric warming and ice vanishing (Haeberli et al. 2010). In the catchments of the Rios Santa, Marañón and Pativilca future new lakes constitute a potential hazard to humans and infrastructures.

Modeling of glacier-bed overdeepenings and possible future lakes forming in such topographic glacier-bed depressions when becoming ice-free was done using the SRTM DEM from the year 2000 with a 90 m resolution and the 2003 glacier outlines from the glacier inventory of the Cordillera Blanca (UGRH 2010). The GIS-based analysis followed three main steps: (1) identification of flat glacier areas with less than 10° surface slope as a first-order spatial approximation to possible occurrences of glacier-bed overdeepenings; (2) application using Google Earth of three morphological indications of glacier-bed overdeepenings following Frey et al. (2010): steepening surface slope, onset of crevasse formation, lateral flow-narrowing; and (3) verification of the results from steps (1) and (2) by comparison with GlabTop modeling of bed topographies (Linsbauer et al. 2012) using the SRTM DEM, contour lines and constructed branch lines for all glaciers of the Cordillear Blanca.

The results show that 31 major new lakes may form in the future with 23 being expected in the catchment of the Rio Santa, 7 in the one of Rio Marañón and 1 in the one of Rio Pativilca. Some of the lakes indeed already started to develop (Figure 1). The total volume of the major potential new lakes is estimated at some 60-65 million m^3. This corresponds to about half a percent of the total glacier volume remaining in the year 2003 and estimated at 15.69 km^3. This relatively small percentage is due to the fact that most flat glacier parts where bed-overdeepenings can be expected have already disappeared.

The procedure applied as a pilot study for the Cordillera Blanca will be used for the other Cordilleras of Peru in order to provide a knowledge and planning basis to the responsible governmental authorities in view of freshwater resources, hazard prevention, energy production and landscape diversity.

REFERENCES

Carey, M., Huggel, C., Bury, J., Portocarrero, C. & Haeberli, W. 2012: An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. Climatic Change112, 3, 733-767.

Frey, H., Haeberli, W., Linsbauer, A., Huggel, C. & Paul, F. 2010: A multi level strategy for anticipating future glacier lake formation and associated hazard potentials. Natural Hazards and Earth System Science 10, 339-352.

Haeberli, W., Clague, J.J., Huggel, C. & Kääb, A. 2010: Hazards from lakes in high-mountain glacier and permafrost regions: Climate change effects and process interactions. Avances de la Geomorphología en España, 2008-2010, XI Reunión Nacional de Geomorphología, Solsona, 439-446.

Linsbauer, A., Paul, F. & Haeberli, W. 2012: Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. Journal of Geophysical Research 117, F03007, doi:10.1029/2011JF002313

UGRH 2010: Inventario de Glaciares Cordillera Blanca, Lima, Perú, Autoridad Nacional del Agua. 120 p.

Figure 1. The flat tongue of Glaciar Artesonraju in the Cordillera Blanca, where a new lake with a considerable volume is likely to form during the coming decades. First stages of lake formation can already be observed at the ice margin. Photograph: D. Colonia, July 2014

P 11.6

Long-term energy balance measurements at three different mountain permafrost sites in the Swiss Alps

Martin Hoelzle[1] & Christian Hauck

[1] *Department of Geosciences, University of Fribourg, Chemin du musée 4, CH-1700 Fribourg (martin.hoelzle@unifr.ch)*

In the framework of the PERMOS permafrost monitoring program, meteorological data is collected at several high altitude sites in the Swiss Alps since the late 1990s. From these stations, three were selected, which are equipped with standard meteorological sensors such as a four component radiation sensor, air temperature, humidity, wind speed and direction as well as ground temperatures and snow height (Hoelzle and Gruber 2008). The energy balance constitutes one of the most important input parameter for the ground heat flux regime, and it is therefore crucial to understand the influence of the individual fluxes. As the individual measurements and the different approaches to calculate the energy balance show large uncertainties, a special focus is laid on the quantification of the uncertainty range of each flux.

All three selected sites differ considerably by their ground material composition. The Murtèl-Corvatsch site (Engadine, Eastern Swiss Alps) is situated on a rock glacier consisting mainly on coarse blocky debris in the active layer followed by an ice supersaturated layer of around 25 m thickness. The Schilthorn site is located at the Northern slope of a mountain summit in the Bernese Alps and is composed by deeply weathered micaceous shales, which are covered by fine grained debris of sandy and silty material. Finally, the Stockhorn site (Southern Valais Alps close to Zermatt) is located on a small plateau slightly inclined to the south and the bedrock consists of Albit-Muskovit schists. It shows at some places the development of patterned ground, especially where the station is located. Based on geophysical soundings the ice content at the Schilthorn and at the Stockhorn plateau sites are estimated to be much less compared to the Murtèl-Corvatsch site.

First results show that the mean surface temperature at Murtèl-Corvatsch (1997-2013) and Schilthorn (1999-2013) are quite similar with -3.23°C and -3.56°C, respectively, whereas at Stockhorn (2002-2013) the surface temperatures are colder with a mean of -8.98°C. The corresponding mean ground temperatures for the same investigation period measured in the PERMOS boreholes are for Murtèl-Corvatsch (0.55 m depth) -0.24°C, Schilthorn (0.2 m depth) -0.07°C and Stockhorn (0.3 m depth) -0.42°C. The measured net radiation is the most important energy input for the surface at each site and shows for Murtèl-Corvatsch 27.31 W m^{-2}, Schilthorn 32.52 W m^{-2} and Stockhorn 22.91 W m^{-2}. The calculated turbulent fluxes based on measurements of wind speed, air temperature and relative humidity using two different approaches (bowen ratio and bulk methods) shows for all sites values of around 8 to 10 W m^{-2} for the Bowen ratio method and 4 to 15 W m^{-2} for the bulk method. Large differences are observed in the energy, which is used for melting the snow cover at the different sites. At Schilthorn a value of 22.86 W m^{-2}, at Murtèl-Corvatsch 11.26 W m^{-2} and at Stockhorn 6.06 W m^{-2} is measured reflecting the different amount of snow depth at these sites. The overall deviation of the energy balance amounts to 10.58 W m^{-2} at Murtèl-Corvatsch, 5.57 W m^{-2} at Schilthorn and 0.06 W m^{-2} at Stockhorn, reflecting also that especially at the Murtèl-Corvatsch site not all fluxes are detected, which confirms recent results by Scherler et al. (2014).

The high temporal variability of the individual fluxes and the additional large uncertainties in the determination of the turbulent heat fluxes (mainly caused by the lack of accurate input conditions of soil moisture contents at the surface as well as reasonable values for the surface roughness) does currently not allow a more precise determination of the whole energy balance in this high alpine terrain. However, the long-term measurement series of the individual fluxes at these sites are a unique prerequisite for detailed modelling studies using these data as validation or as calibration measures.

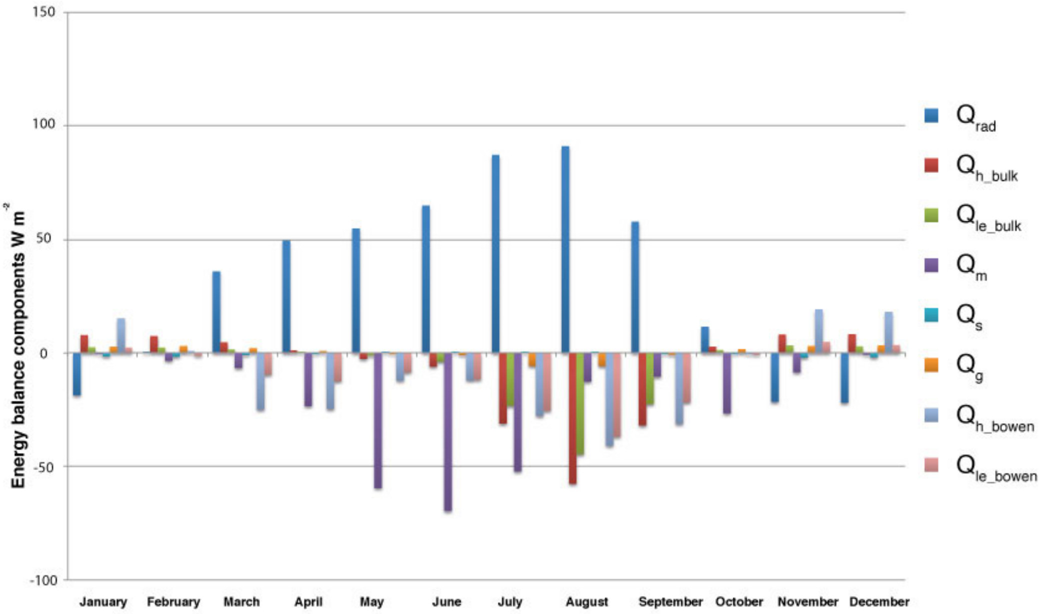


Figure 1. Mean of all energy balance components calculated for the Schilthorn site for the period 1999-2013.

REFERENCES

Scherler, M, Schneider, S., Hoelzle, M. and Hauck, C. 2013: A two-sided approach to estimate heat transfer processes within the active layer of rock glacier Murtèl-Corvatsch. Earth Surface Dynamics Discussion, 1, 141-175.

Hoelzle, M. and Gruber, S. 2008: Borehole and ground surface temperatures and their relationship to meteorological conditions in the Swiss Alps. Ninth International Conference on Permafrost, Fairbanks, Alaska, 1, 723-728.

P 11.7

Swiss glaciers: TanDEM-X time series vs. SwissAlti3D

Silvan Leinss[1], Irena Hajnsek[1,2]

[1] *Institut für Umweltingenieurwissenschaften (IfU), ETH Zürich, Stefano-Franscini-Platz 3, 8093 Zürich (leinss@ifu.baug.ethz.ch)*
[2] *Microwaves and Radar Institute, German Aerospace Center (DLR), Germany*

High precision digital elevation models (DEMs), derived from air- and space-borne sensors have reached a vertical accuracy on the meter scale. The precision is pushing towards the scale, on which glaciers and even the seasonal snow cover changes during one year. Therefore, a comparison of digital elevation models allows to monitor volume changes of glaciers and snow cover. Due to the vertical precision and the fast changes of snow and glaciers, knowledge of the exact date of the acquisitions as well as the penetration depth in case of radar based methods is of high importance.

The SwissAlti3D is up to now the best available DEM for Switzerland and is updated every six years with airborne stereographic and lidar data of the past few years, if necessary. However, it is composed of very different data sources where the exact date of acquisition is not necessarily available and complicates therefore short-term comparisons.

The TanDEM-X satellite mission [Krieger 2007, Krieger 2010], build create a high precision globe-spanning DEM (the so called WorldDEM™), acquired all data within three years to provide a globally consistent digital elevation model. The DEM is based on singlepass SAR-Interferometry, which uses a radar frequency of 9.65 GHz. This frequency has been chosen, to provide a spatial resolution of a few meter and to avoid too much penetration into the underlying ground. However, the penetration into snow is a crucial parameter and can reach a couple of meters for very dry and cold snow [Davis, 1993]. However, it quickly changes as soon as the moisture content within the snow volume increases above a fraction of a percent [Abe, 1990] where the penetration depth is not more than few cm.

I will present a comparison of the SwissAlti3D with TanDEM-X acquisition from various glaciers of Switzerland (Aletsch-, Findelen-, Gorner-, Rhonegletscher). Further, I will show results from TanDEM-X time series, with an acquisition every 11 days. TanDEM-X time series of Aletsch- and Rhonegletscher have been calibrated by a large number of reference points to get a vertical resolution on the sub-meter scale.

The time series show annual oscillations due to snow accumulation and snow and ice melt. The comparison of data from different years shows an average volume/height loss of 3 - 4 meter per year.

A comparison of autumn with spring acquisitions allows to derive snow accumulation maps. Fresh snow accumulation of 3 - 5 meter per year have been determined.

The penetration depth can be estimated from sudden changes in the height but also from changes in the backscatter signal which indicates the transition from dry to wet snow. Penetration depths for dry snow of up to 7 meter have been found.

REFERENCES

G. Krieger, I. Hajnsek, K. Papathanassiou, M. Younis, and A. Moreira, "Interferometric synthetic aperture radar (SAR) missions employing formation flying," Proceedings of the IEEE, vol. 98, no. 5, pp. 816–843, 2010.

G. Krieger, H. Fiedler, M. Zink, I. Hajnsek, M. Younis, S. Huber, M. Bachmann, J. Hueso Gonzalez, M.Werner, and A. Moreira, "TanDEM-X: A satellite formation for high-resolution SAR interferometry," IEEE transactions on geoscience and remote sensing, vol. 45, no. 11, pp. 3317–3341, November 2007.

C. Davis and V. Poznyak, "The depth of penetration in antarctic firn at 10 GHz," IEEE Transactions on Geoscience and Remote Sensing, vol. 31, no. 5, pp.
1107 –1111, 1993.

T. Abe, Y. Yamaguchi, and M. Sengoku, "Experimental study of microwave transmission in snowpack," IEEE Transactions on Geoscience and Remote
Sensing, vol. 28, no. 5, pp. 915 –921, 1990.

P 11.8

Evaluation of automatic weather station data to observe the characteristics and changes in glacier surface albedo

Kathrin Naegeli[1], Matthias Huss[1] & Martin Hoelzle[1]

[1] *Department of Geosciences, University of Fribourg, Switzerland (kathrin.naegeli@unifr.ch)*

The albedo has a major impact on the energy balance of a glacier surface. It mainly influences the amount of absorbed/reflected radiation and is therefore a major controlling factor of surface melt especially during the ablation period. The glacier surface in the ablation area itself is not only consisting on pure ice surface but depends in a complicated way on many factors, such as cryoconite concentration, impurities due to mineral dust, soot or organic matter, amount of liquid water, grain size or ice surface morphology. Several studies have focused on temporal and spatial variations of albedo and its importance in calculating the energy balance of a glacier surface [e.g. Oerlemans and Klok, 2002; Jonsell et al., 2003; Brock, 2004] and more recently on cryoconite composition [e.g. Casey et al., 2012] and glacier surface mapping [e.g. Chandler et al., 2014]. However, still fairly little is known about the state, changes and impact of glacier surface albedo in the Swiss Alps, which is particularly critical since there are obvious changes in surface characteristics on most alpine glaciers over the last years.

To study the characteristics and changes of glacier surface albedo various measurements were conducted throughout the ablation seasons on Glacier de la Plaine Morte in 2013 and 2014. Adjacent to repeated portable albedo measurements along profiles, ice melt was intensively monitored using over 20 ablation stakes distributed along these profiles but also randomly places in dark and bright ice areas of the glacier. Additionally, cryoconite samples were collected to obtain more information about the composition of the surface materials. Moreover, an automatic weather station measuring air and ice temperatures, relative humidity, wind speed and direction, precipitation as well as the four radiation components was installed on the winter snow surface in the beginning of July and dismantled in late fall, measuring the climate variables at a temporal resolution of 10 minutes.

In the context of this ongoing work, we present first evaluations of these climate variable data with a special focus on the temporal evolution of glacier surface albedo, most prominently the snow-ice transition in beginning of August, but also the impact of snowfall events throughout the ablation season. Furthermore, the spatial variations of glacier surface albedo are analysed combining the repeated albedo point measurements with the spatially distributed ablation measurements and collected cryoconite samples.

REFERENCES

Brock, B.W. 2004: An analysis of short-term albedo variations at Haut Glacier d'Arolla, Switzerland. Geografiska Annaler, 86(1), 53–65.

Casey, K., Kääb, A. & Benn, D.I. 2012: Geochemical characterization of supraglacial debris via in situ and optical remote sensing methods: a case study in Khumbu Himalaya, Nepal. The Cryosphere, 6(1), 85–100.

Chandler, D.M., Alcock, J.D., Wadham, J.L., Mackie, S.L. & Telling, J. 2014: Seasonal changes of ice surface characteristics and productivity in the ablation zone of the Greenland Ice Sheet. The Cryosphere Discussion, 8(1), 1337–1382.

Jonsell, U., Hock, R. & Holmgren, B. 2003: Spatial and temporal variations in albedo on Storglaciären, Sweden. Journal of Glaciology, 49(164), 59–68.

Oerlemans, J. & Klok, E.J.L. 2002: Energy balance of a glacier surface: analysis of autmatic weather station data from the Morteratschgletscher, Switzerland. Arctic, Antarctic, and Alpine Research, 34(4), 477–485.

P 11.9

10 years of MB measurements on Findelengletscher, VS, Switzerland

Nadine Salzmann[1], Matthias Huss[1], Horst Machguth[2], Leo Sold[1], Andreas Linsbauer[1], Philip Jörg[3], Gwendolyn Leysinger-Vieli[3], Martin Hoelzle[1]

[1] Department of Geosciences, University of Fribourg, Chemin de Musée 4, CH-1700 Fribourg (nadine.salzmann@unifr.ch)
[2] Department of Civil Engineering, Technical University of Denmark, Brovej 18, DK-2800
[3] Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich

Mass balance observations on Findelengletscher were started in 2004 (Machguth et al. 2006). At that time, the main objective for the measurements was the generation of reference data for the validation and calibration of a mass balance model, rather than for the purpose of a long-term mass balance programme. In 2009, the Universities of Fribourg and Zurich decided to jointly start a long-term mass balance monitoring programme on Findelengletscher (and the nearby Adlergletscher), because of its ideal setting. Findelengletscher is relatively large (about 13km²), easily accessible and has an almost debris-free surface. Since 2009, summer and winter mass balance was measured each year using state-of-the-art in-situ methods. In addition, high-resolution digital elevation models are available for the years 2005, 2009, 2010 and 2012.

Moreover, a number of other studies are ongoing related to glacier monitoring, such as an improved representation of winter snow accumulation distribution by means of helicopter-borne ground-penetrating radar and the remote determination of firn layer thickness (Sold et al. 2013, 2014). Furthermore, several subsurface monitoring projects are located In the vicinity of Findelengletscher, at the PERMOS site (PERmafrost MOnitoring Switzerland) at Stockhorn. The combined permafrost and glacier monitoring activities provide a great basis for integrated cryospheric analyses.

Here, we present a complete and homogenous evaluation of the 10-year seasonal mass balance time series of Findelen and Adlergletscher. We apply and compare different approaches for the calculation of glacier-wide mass balance from point field measurements (contour line and profile method, modelling). Results are validated against independent ice volume changes for the period 2005-2010 (Joerg et al. 2012). By including all available information (winter accumulation distribution, annual mass balance, and meteorological data) into an integrated scheme for mass balance evaluation, good agreement with the geodetic method is found and allows us to present a re-analyzed series of the 10-year monitoring activities on Findelengletscher. In addition, we compare the results for Findelen and Adlergletscher with other long-term series included in the Swiss glacier monitoring network and discuss the differences with respect to recent climate change in the Alps.

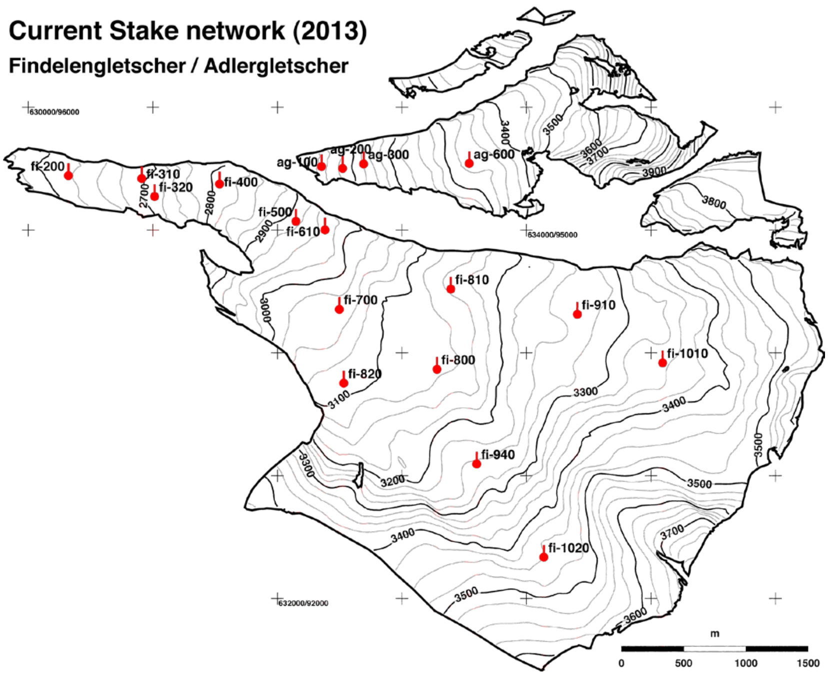


Figure 1. Current stake network and glacier outlines of Findelen and Adlergletscher.

REFERENCES

Joerg, P.C., Morsdorf, F. & Zemp, M. (2012): Uncertainty assessment of multi-temporal airborne laser scanning data: A case study on an Alpine glacier. Remote Sensing of Environment, 127, 118-129.

Machguth, H., Eisen, O., Paul, F. & Hoelzle, M. (2006): Strong spatial variability of snow accumulation observed with helicopter-borne GPR on two adjacent Alpine glaciers. Geophysical Research Letters 33, L13503.

Sold, L., Huss, M., Hoelzle, M., Andereggen, H. Joerg, P. C., & Zemp, M. 2013: Methodological approaches to infer end-of-winter snow distribution on alpine glaciers. Journal of Glaciology, 59(218), 1047–1059, doi:10.3189/2013JoG13J015.

Sold, L., Huss, M., Eichler, A., Schwikowski, M. & Hoelzle, M. 2014. Recent accumulation rates of an alpine glacier derived from firn cores and repeated helicopter-borne GPR. The Cryosphere Discuss., 8, 4431-4462, doi:10.5194/tcd-8-4431-2014.

P 11.10

Measuring snow surface topologies and its changes using Microsoft's Kinect

Philip Crivelli[1], Stefan Horender[1,2], Enrico Paterna[1], Michael Lehning[1,3]

[1] *WSL Institute for Snow and Avalanche Research, SLF Davos, Flüelastrasse 11, CH-7260 Davos, Switzerland (philip.crivelli@slf.ch)*
[2] *TROPOS, Leibniz-Institut für Troposphärenforschung, Permoserstrasse 15, 04318 Leipzig, Germany*
[3] *CRYOS, School of Architecture, Civil and Environmental Engineering, Ecole Polytechnique Federal de Lausanne, Lausanne*

The evolution of the snow surface during a snow drift event in a cold wind tunnel was recorded with Microsoft's Kinect device. Microsoft's Kinect device can be used as a low cost alternative to common three dimensional scanners. Since its introduction as a tool for video games, the scientific community gained more and more interest in its applications. To validate its performance, we first measured the topology of a small hill consisting of either sand or fresh snow and compared the Kinect 3D results with a profile through the hill obtained by shadow images. We found that this setup can record the snow surface with a satisfying precision in the range of millimeters.

Previously, experimentally recording snowdrift was done with different tools such as snow particle counters (SPC), shadow graphic imaginary, acoustic devices (FlowCapt), impact sensors, or particle traps. These tools can represent a flux profile or a point measurement. We propose to use Microsoft's Kinect device as a tool to analyze the surface change during snowdrift events. To the authors' knowledge, no studies have been performed that document quantitatively the processes on the snow surface during snow drift in such a large control volume in a wind tunnel.

We present the evolution of a snow surface during a drifting snow event and calculate a mass flux from the mass balance for a defined control volume.

Outlook: we also will try to measure surface ripples and "mini" zastrugi formed during drifting snow experiments, since the nearly instantaneous break down of these structures may lead to large fluctuations in the drifting mass flux, as has been observed earlier.

P 11.11

Ground thermal regime and its relation to snow cover in Alpine rock walls

Anna Haberkorn[1,2], Marcia Phillips[1], Robert Kenner[1], Hansueli Rhyner[1], Martin Hoelzle[2]

[1] *WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos (haberkorn@slf.ch)*
[2] *Department of Geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg*

Changes in rock temperature and variability in the ice and water content of permafrost rock walls can lead to rock wall instability. Rising air temperatures and consequently rock temperatures are key control factors of permafrost degradation. Additionally the thickness and duration of the heterogeneously distributed and patchy snow cover in high alpine mountain regions alters the evolution of ground surface temperatures, since the snow influences the energy balance of the ground due to changes of both the radiation budget and turbulent fluxes of sensible and latent heat at the ground surface.

The majority of steep mountain rock slopes are usually non-vertical, fractured and variable inclined. Consequently a strong spatial and temporal variable snow cover is likely to exist and its depth depends on the slope angle, aspect, surface roughness and surface concavity. The snow cover either has an insulating or cooling effect on rock temperatures, depending on its thickness (Hoelzle et. al, 2003). The snow cover significantly affects the energy balance and water supply, thus altering the ice and water content of the rock wall discontinuities, which can lead to rock instabilities.

To assess the temporal and spatial evolution and distribution of the snowpack and the corresponding influence on the rock thermal regime several south and north facing permafrost rock walls in the Swiss Alps have been investigated since 2012. To obtain information on both rock temperatures and on snow cover duration, near-surface rock temperature (*NSRT*) measurements are carried out in 10 cm depth, using iButtons. Snow cover stratigraphy and temperatures are investigated in-situ with snow pits. Automatic cameras register snow distribution and weather conditions hourly. Terrestrial laser scans (*TLS*) are carried out to obtain the depth and the spatial distribution of the snow cover at regular intervals and borehole temperatures are measured to determine the influence of the snow cover at depth at one particular site. *NSRT* measurements in steep rock slopes provide valuable information on the thermal regime of the rock surface and on snow cover distribution, which are both highly dependent on aspect, slope, shading effects and surface roughness. The south facing slopes are subject to high daily temperature variations of up to 20 °C in summer and winter, if no snow can accumulate, whereas *NSRT* remains close to 0 °C under snowpack conditions without permafrost beneath (see Figure 1). On these rock slopes the snow cover typically consists of rounded grains, melt crusts and ice lenses at the snow-rock interface. *NSRT* on the north facing slopes are closely linked to air temperature under snow-free conditions, while the *NSRT* data indicate a delayed and damped atmospheric signal under a thick snowpack. On these slopes the winter snowpack typically consists of faceted crystals and depth hoar. No decrease of snow depth with slope angles up to 70° were observed by *TLS* in rough terrain due to micro-topographic structures. All aspects and angles can accumulate ephemeral rime during storms.

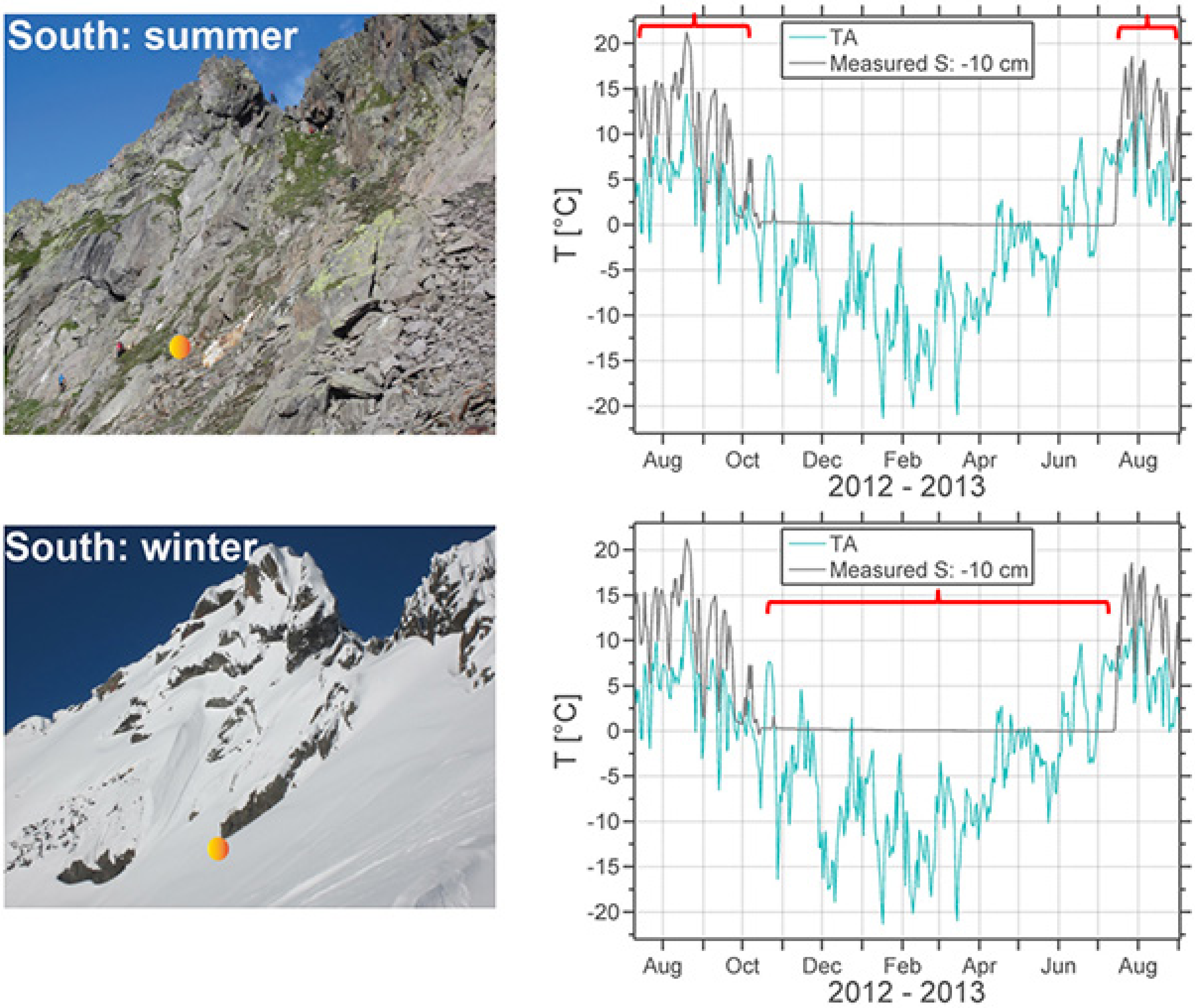


Figure 1. One year of data of *NSRT* measured at a south facing rock wall in summer (top) and winter (bottom) and air temperature (TA) measured at an adjacent automatic weather station. The orange circles indicate the measurment location, whereas the red brackets highlight the summer and winter season.

REFERENCES

Hoelzle, M., Haeberli, W. & Stocker-Mittaz, C. 2003: Miniature ground temperature data logger measurements 2000-2002 in the Murtèl-Corvatsch area, Eastern Swiss Alps. In: Phillips, M., Springman, S. and Arenson, L. (eds), Proceedings of the 8th International Conference on Permafrost, Swets & Zeitlinger, Lisse, 419-424.

P 11.12

Extended-range probabilistic forecasts of snow water equivalent and runoff in mountainous areas

Jörg-Hess Stefanie[1], Griessinger Nena[2], Zappa Massimiliano[1]

[1] *Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf (stefanie.joerg@wsl.ch)*
[2] *Swiss Federal Research Institute WSL/SLF, Flüelastrasse 11, CH-7260 Davos Dorf*

Good initial states can improve the skill of hydrological ensemble predictions. Better hydrological forecasts can be produced with better estimates of snow storage. In mountainous regions such as Switzerland, snow is an important component of the hydrological system. Including estimates of snow cover in hydrological models is of great significance for the prediction of both flood and stream flow drought events. In this study, gridded snow water equivalent maps (SWE maps), derived from daily snow depth measurements, are used within the gridded version of the conceptual hydrological model PREVAH to replace the model SWE at initialization (Figure 1). The ECMWF VarEPS reforecast is used as meteorological input for 32 day forecasts of stream flow and SWE. Experiments were performed in several parts of the Alpine Rhine and the Thur rivers. Predictions with the imported SWE maps could successfully enhance the predictability of SWE up to a lead time of 25 days, especially at the beginning and the end of the snow season. Additionally, the prediction of the runoff volume was improved, particularly in catchments where the snow accumulation, and thus the runoff volume had been greatly overestimated. These improvements in predictions have been made, without affecting the ability of the forecast system to discriminate between the different runoff volumes observed. Evaluations of spatial similarity were applied in this study for the first time in water resource forecasting.

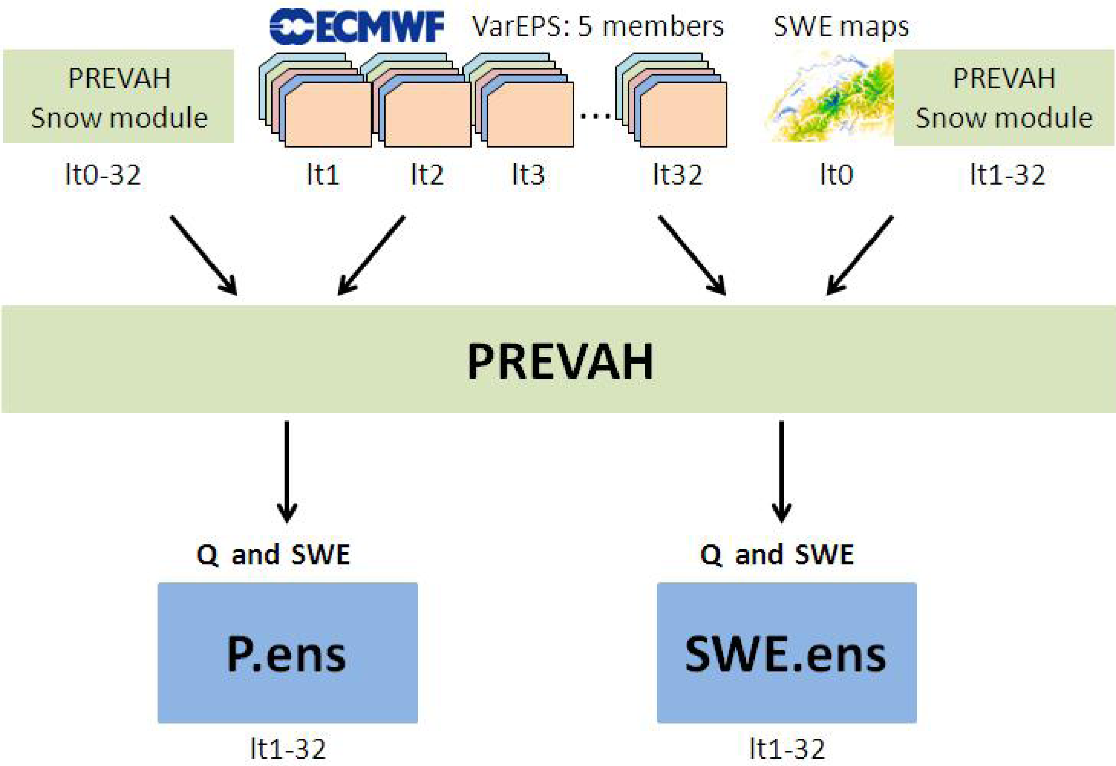


Figure 1: Setup for the simulations of runoff and SWE. Predictions with the hydrological model PREVAH are forced with the ensemble numerical weather prediction VarEPS. Predictions for the lead times 1-32 (lt 1-32) that use the simulated SWE from PREVAH are denoted P.ens, and those that imported SWE maps at initialization SWE.ens.

P 11.13

Projections of permafrost evolution in the Swiss Alps coupling climate and soil models

Antoine Marmy[1], Jan Rajczak[2], Sven Kotlarski[2], Nadine Salzmann[1], Christian Hauck[1]

[1] *Alpine Cryosphere and Geomorphology Group, Department of Geosciences, University of Fribourg, Switzerland*
[2] *Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland*

In the context of a global climate warming, the long-term modelling of permafrost in the Swiss Alps is one of the most challenging but also one of the most interesting research topics. The challenge of long-term modelling of permafrost in mountain areas relates to the scarcity of reliable onsite meteorological data as well as subsurface ground temperature time series making the calibration procedure tricky. In this contribution, we present the results of the calibration and the long-term modelling of 5 permafrost sites in the Swiss Alps: Lapires, Schilthorn, Stockhorn, Ritigraben and Murtel, covering a broad range of morphological characteristics including rock slopes, talus slopes ans rock glaciers.

The calibration of the soil model COUP has been carried out for all sites using the General Likelihood Uncertainty Estimation (GLUE) method (Jansson 2012), an inverse modelling approach testing a multitude of parameter combinations to find the parameter set giving the best fit with the observations. The parameters used for calibration concern both the upper boundary conditions (snow and albedo) and subsurface parameters (such as porosity, thermal and hydraulic conductivities). Once the calibration is considered satisfactory, the model has been run for all sites until the end of the 21st century using downscaled climate model outputs driven by the A1B scenario for 14 different GCM/RCM chains. The statistical downscaling approach employed include a 2-step bias-correction procedure: first, downscaling of simulated RCM time series for several meteorological variables to high-quality MeteoSwiss stations using quantile mapping and, second, a further quantile mapping step between the MeteoSwiss stations and the corresponding on-site meteorological data of the permafrost stations.

The resulting projections of ground temperature change, active layer thickness and snow cover duration are compared among the different sites and among different GCM/RCM chains.

REFERENCES

Jansson, P.E. 2012: CoupModel: Model use, calibration and validation. Trans. ASABE 55 1335-1344.

P 11.14

Long term monitoring of the Mont Dolin rock glacier (Swiss Alps)

Nendaz Thierry[1], Lambiel Christophe[1]

[1] *Institut des dynamiques de la surface terrestre, Université de Lausanne, Mouline – Géopolis, 1015 Lausanne (thierry.nendaz@unil.ch)*

The current global climate change implies some perturbations in permafrost environments. The dynamics of landforms like rock glaciers can, therefore, be modified due to the climatic changes. However, the response to climate change is different from site to site because of the importance of both local (e.g. solar radiation) and regional (e.g. precipitations, annual temperature) factors.

The Mont Dolin talus rock glacier is located in a south-oriented glacial cirque in Arolla (VS). Using differential GPS surveys and photogrammetric data, this study provides a long term monitoring of this rock glacier. In addition, Electrical Resistivity Tomographies (ERT) have been carried out in summer 2013 to define its current internal structure and especially the distribution of permafrost. Results suggest a weak geomorphic activity, illustrated by decimetric topographical changes in the past fifty years, and by the very slow (up to 9 cm per year) permafrost creep during the last decade. The ERT results suggest the presence of massive ice at the limit between the rock glacier and the talus slope. Moreover, ice content tends to decrease from this spot up to the front of the rock glacier.

Located at the lower limit of the permafrost belt, the Mont Dolin rock glacier seems to be undergoing fossilisation. Furthermore, the link between ice content and geomorphic activity is not obvious. The sediment supply due to gravity seems to be the most important factor in areas where the thickness has increased.

P 11.15

Gap filling procedures for ground surface temperature time series of the PERMOS network

Staub Benno[1], Hasler Andreas[1], Delaloye Reynald[1]

[1] *Département Géosciences, Unité Géographie, Université de Fribourg, Chemin du Musée 4, CH-1700 Fribourg (benno.staub@unifr.ch)*

The acquisition of permafrost monitoring data in high mountain environments like the Swiss Alps is complicated by technical issues related to the rough terrain and climate as well as limited accessibility and budget. As a result, many of these time series are interrupted by gaps of different duration (hours-years) what complicates the calculation of aggregates and indices. In the frame of the SNSF Sinergia project «The Evolution of Mountain Permafrost in Switzerland» (TEMPS, 2011–2014), a variety of processing routines are developed for data homogenization and analysis that can – in a further step – be operationalized in the Swiss Permafrost Monitoring Network (PERMOS).

The major aim behind this initiative is to get continuous time series of daily mean ground surface temperatures (GST) to allow analyses on the basis of running annual means (rMAGST) and indices like thawing and freezing degree days (TDD, FDD). Using complete GST time series and a large number of randomly generated synthetic gaps, the performance of various interpolation, regression and bias-correction techniques as well as approaches to quantify the uncertainty resulting on aggregates and indices are assessed.

Linear regression and quantile mapping have shown to be the most reliable gap filling approaches for daily mean GST records, but up to gap durations of one week linear interpolation is not significantly worse. Gaps that are affected by snow melt in spring or longer than three months require individual treatment separately for each season (depending on the snow cover evolution). To fill entire years, increasing the temporal resolution to weekly means seems promising. Finding the best regressor loggers is crucial and also the main source of uncertainty. Because the similarity of GST time series depends rather on site-specific characteristics like the surface type or topoclimatic properties than spatial proximity, all kinds of surface temperature records from a variety of study sites should be included, also borehole temperatures measured close to the surface. The integration of the procedure into the PERMOS data base has a high potential, also because additional data measured in the future might improve the quality of several hundred temperature time series from the past.

P 11.16

Spatial and temporal variability of soil moisture in permanently frozen ground at Schilthorn (Swiss Alps)

Adrian Wicki[1], Christian Hauck[1], Cécile Pellet[1], Christin Hilbich[1], Andreas Kemna[2], Maximilian Weigand[2] & Sebastian Wege[2]

[1] Department of Geosciences, University of Fribourg, Chemin de Musée 4, CH-1070 Fribourg (adrian.wicki@unifr.ch)
[2] Department of Geodynamics and Geophysics, University of Bonn, Meckenheimer Allee 176, D-53115 Bonn

The thermal behaviour of permanently frozen ground is largely influenced by the presence of soil moisture. However, especially in high mountain environments, the subsurface and therefore the spatial distribution of soil moisture can be very heterogeneous. As a consequence, the thermal regime of permafrost soils can vary significantly within some meters. Such small scale temperature variations are identified at the PERMOS permafrost research station on the Schilthorn summit (Swiss Alps). At two borehole locations, situated in the northern slope of the summit, subsurface temperatures are measured down to 14m and 100m depth, respectively. Although the two boreholes are only 15m apart, the thermal behaviour in the uppermost meters shows significantly different characteristics. Several studies suggested different soil moisture regimes as the main explanatory factor (Völksch 2004, Hilbich et al. 2011).

In this study, the spatial and temporal variability of soil moisture and ground ice in the slope above and in the vicinity of the boreholes is studied during summer 2014. More precisely, it aims at detecting percolation depths, possible preferential flow paths and the influence of subsurface features such as the presence of bedrock outcrops on groundwater flow. Furthermore, the results are set into a meteorological context in order to account for the temporal variability.

For this purpose, Electrical Resistivity Tomography (ERT) profiles are measured at several locations upslope of the boreholes. The measurements are repeated at various times throughout the summer when the surface is partly snow covered as well as snow-free. The resulting 2-D tomograms of specific electrical resistivity can be related to the spatial variability of soil moisture and ground ice at depths to 7 meters. Additionally, the temporal changes of the soil moisture distribution are calculated using a time-lapse inversion scheme. Finally, using Archie's law (Archie 1942), the soil moisture is quantified from the ERT measurements, where in-situ soil moisture data are used for calibration. This approach can also be used for existing data of the permanent ERT profile line, along which electrical resistivity is measured at a coarser resolution since 1999 (Hilbich et al. 2011).

As validation for the soil moisture dynamics derived from ERT, continuous measurements provided by Time Domain and Frequency Domain Reflectometry (TDR, FDR) sensors installed in the vicinity of the boreholes are used. In addition, continuous Self-Potential (SP) measurements conducted within the study area are used for the identification of preferential flow paths and the characterization of subsurface flow dynamics, which in turn can be related to the spatio-temporal soil moisture variations. Finally, soil moisture measeuements will be conducted on soil samples from several locations. The results of the spatio-temporal soil moisture analysis are compared to meteorological conditions during summer 2014 in order to assess the impact of snow melt and precipitation events on the hydrological regime. The work is used as a base for further studies on the influence of soil moisture on the thermal behaviour of permafrost.

REFERENCES

Archie, G. E. 1942: The electrical resitivity log as an aid in determining some reservoir characteristics, Petroleum Transactions of American Institute of Mining and Metallurgical Engineers (AIME),146, 54–62.

Hilbich, C., Fuss, C. & Hauck C. 2011: Automated Time-lapse ERT for Improved Process Analysis and Monitoring of Frozen Ground. Permafrost and Periglacial Processes 22, 306-319.

Völksch, I. 2004: Untersuchung und Modellierung kleinräumiger Unterschiede im Verhalten von Gebirgspermafrost. Diploma thesis ETH Zürich.

P 11.17

Antarctic snow stratigraphy - new methods and insights

Martin Schneebeli[1], Martin Proksch[1], Margret Matzl[1], Stefanie Weissbach[2]

[1] *WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland (schneebeli@slf.ch)*
[2] *Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany*

The stratigraphy in Antarctica is a complex product of depositional and metamorphic processes. The depositional process is dominated by frequent re-deposition and rare atmospheric precipitation. Metamorphism is a ubiquitous and significant process occurring at the near surface of snow and firn. Relatively little is known about how snow metamorphism affects the physical and mechanical properties of snow in Antarctica, and observations are difficult by traditional means. One reason for the lack of knowledge is that depositional and metamorphic processes occur concurrently. Near-infrared photography, quantitative translucent profiles, high-resolution penetrometry, optical Specific Surface Area measuring instruments and micro-tomography are modern methods suitable for use in Antarctic snowpacks. These instruments gather detailed stratigraphic information at multiple scales. We applied these methods at three different sites in Antarctica: Allan Hills, Pointe Barnola and Kohnen Station. The characteristic stratigraphy and microstructures found at these locations will be presented and interpreted. The new methods are very efficient to reveal the complex structures. Based on our observations, we show that alternating temperature gradient metamorphism, which is the dominant type of metamorphism at the surface, has a strong effect on the re-mobilization of the hard snow surface during austral summer, and temperature gradient metamorphism is important during winter. Large erosional events, removing multiple years of deposition, can occur, and have a marked impact on stratigraphy.

P 11.18

Snow microstructure and modelling in support of permafrost science

Martin Proksch[1,4], Isabelle Gouttevin[2], Moritz Langer[3], Pirmin Ebner[1], Charles Fierz[1], Martin Schneebeli[1]

[1] *WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf (proksch@slf.ch)*
[2] *Laboratory of Cryospheric Sciences CRYOS, Ecole polytechnique fédérale de Lausanne EPFL, CH-1015 Lausanne*
[3] *Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Research Unit Potsdam, Telegrafenberg A 43, 14473 Potsdam, Germany*
[4] *Institute for Meteorology and Geophysics IMGI, University of Innsbruck, Innrain 52f, 6020 Innsbruck*

Permafrost underlies ~22% of the Northern Hemisphere ground surface and has been observed and projected to undergo severe degradation in the context of global warming. Yet, permafrost modelling is still a challenging task, even at monitoring stations where observations of ground properties exist. One of the main locks is the representation of the thermal properties of snow, which very much depend on snow microstructure and accumulation depth.

Here, we present the results of a spring campain lead on Samoylov Island, Lena Delta (72.4°N, 126.5°E), Siberia, where snow was investigated in terms of stratigraphy and microstructural parameters. Several snow profiles and transects were measured in order to characterise the snow over the polygonal tundra landscape. Cast snow samples were analysed by micro-computed tomography in the cold laboratory at SLF, Davos in order to calculate physical properties for relevant transport processes in the snowpack, such as thermal conductivity and permeability.

Additionally, the snow cover model SNOWPACK is applied at Samoylov, to assess its capability to represent a high-arctic snowpack. Overall, SNOWPACK predicts realistic profiles of physical and structural properties similar to the observed ones. This is an encouraging step for the application of snow modelling in support of the permafrost science community.

P 11.19

Imaging of snow algae in natural snow using phase-contrast tomography

Mareike Wiese[1] & Martin Schneebeli[1]

[1] *WSL-Institut für Schnee- und Lawinenforschung, Flüelastrasse 11, CH-7260 Davos Dorf (mareike.wiese@slf.ch)*

Snow algae influence the radiative properties of snow. Snow with algal blooms often appears red and hence darker than snow without algae. These algae commonly occur on melting snow, but little is known about the precise location of the algae within the snow and their life-cycle and micro-habitat.

We took snow samples with snow algae in the Swiss Alps. Using phase-contrast tomography, we investigate whether we can find snow algae inside the snow samples with this imaging technique to get more information about their micro-habitat.

In the resulting images we can identify small particles of the typical size of snow algae (about 20 micrometer in diameter) besides the larger ice structure of the snow. Interestingly, the snow algae are located on the surface of snow grains. This finding supports the suggestion that snow algae migrate from the ground into the snow towards the snow surface, moving on the liquid water film on the surface of snow grains.

P 11.20

The contribution of locally extreme snow depths to the winter snow cover volume of Alpine glaciers in the Ötztal Alps, Austria

Kay Helfricht[1,2] Michael Lehning[3,4] Rudolf Sailer[5] & Michael Kuhn[2]

[1] *IGF - Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences Technikerstr. 21a, A-6020 Innsbruck (kay.helfricht@oeaw.ac.at)*
[2] *Institute of Meteorology and Geophysics, University of Innsbruck, Innrain 52f, A-6020 Innsbruck*
[3] *WSL, Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf*
[4] *CRYOS, School of Architecture, Civil and Environmental Engineering, EPFL, GR A0 402 (Bâtiment GR), Station 2, CH-1015 Lausanne*
[5] *Institute of Geography, University of Innsbruck, Innrain 52f, A-6020 Innsbruck*

Snow deposition and redistribution are major drivers of snow cover dynamics in mountainous terrain and play a major role in the mass balance of Alpine glaciers. The quantitative understanding of inhomogeneous snow distribution in mountains has recently benefited from advances in measuring technologies, such as laser scanning (lidar, e.g. Deems et al. 2013), but also from increased understanding of the physical processes. This contribution further advances the quantitative understanding of uneven snow distribution on glaciers by analysing the areas of maximum snow depth in a mountain catchment with large and small glaciers.

We analysed multi-temporal airborne laser scanning (ALS) data with a high spatial resolution to investigate the contribution of locally extreme snow depths to seasonal snow volume on glaciers in a large part of the Ötztal Alps and for several glaciers in a partly glacierized subcatchment.

Using multi-annual ALS observations, we found that maximum snow depths occur on rather thin borders along the glacier margin in the glacier accumulation zone. While snow depth distribution patterns in less extreme terrain have presented high inter-annual persistence, there is little persistence between winters of those extreme glacier accumulations. We therefore interpret the lack of persistence as the result of a predominance of gravity-driven redistribution (avalanches and sloughs), which has an inherently higher random component because it does not occur with all conditions in all winters. We further suggest that these extreme accumulations play a significant role in the glacier mass balance and that they may be successfully parameterized by simple mass redistribution algorithms, which have been presented in the literature (e.g. Gruber, 2007; Bernhardt and Schulz, 2010)

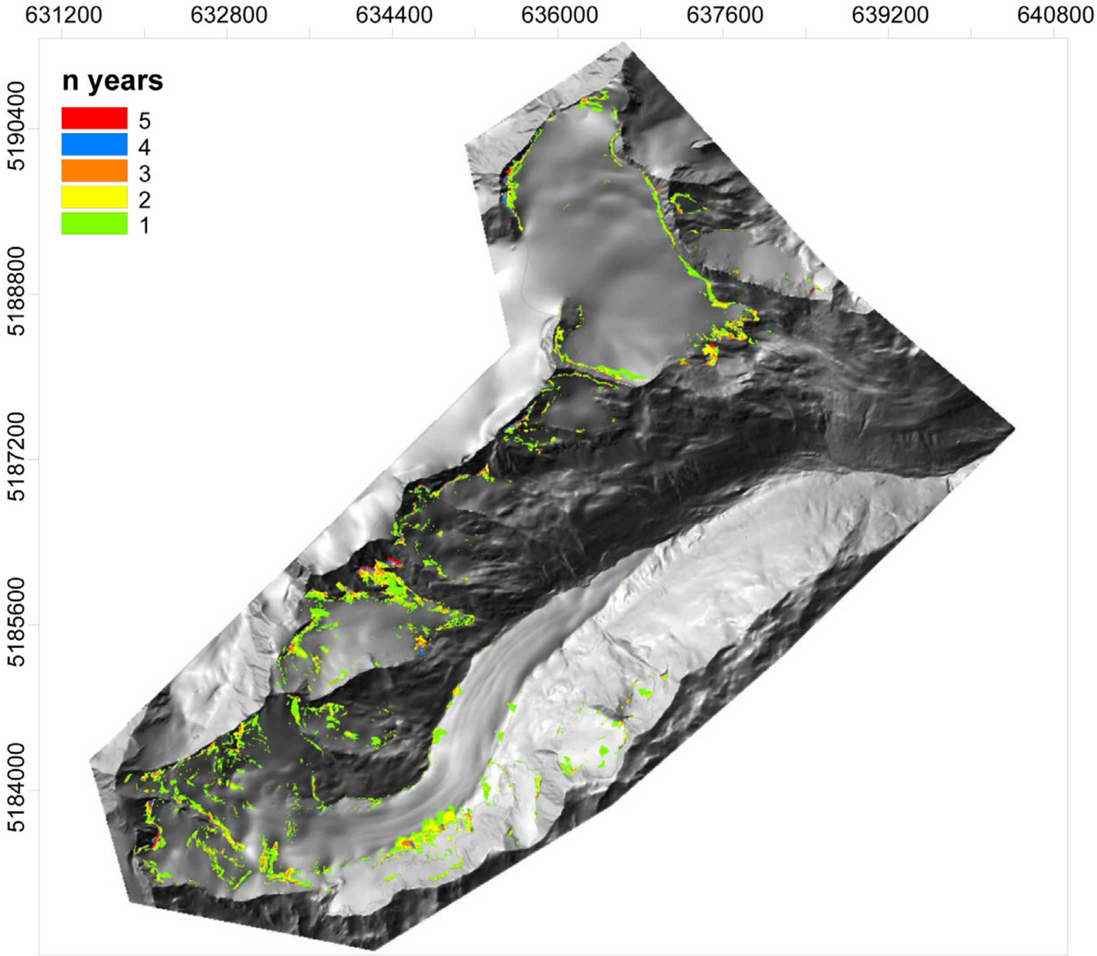


Figure 1. Distribution of areas affected by extreme snow depths on glacier surface by the number of years they occurred.

REFERENCES

Bernhardt, M. & Schulz, K., 2010. Snowslide: A simple routine for calculating gravitational snow transport. Geophysical Research Letters, 37(11), L11502.

Deems, J., Paintner, T., & Finnegan, D., 2013. Lidar measurement of snow depth: a review. Journal of Glaciology, 59(215), 467–479.

Gruber, S., 2007. A mass-conserving fast algorithm to parameterize gravitational transport and deposition using digital elevation models. Water Resources Research, 43(6).

P 11.21

Towards a better representation of snow accumulation distribution in glacier mass balance models

Leo Sold[1], Matthias Huss[1,2], Martin Hoelzle[1]

[1] *Department of Geosciences, University of Fribourg, Ch. du Musée 4, CH-1700 Fribourg (leo.sold@unifr.ch)*
[2] *Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich, Wolfgang-Pauli-Strasse 27, CH-8093 Zürich*

Snow accumulation is a key variable in glacier mass balance modelling approaches. Its spatial distribution controls melt-out patterns and spatio-temporal surface albedo variations. If measurements of snow accumulation distribution exist they typically consist of probings and snow density pits. Because such surveys are time-consuming and laborious, measurements are sparse and can hardly be representative for large or medium-sized glaciers. If no observations are available, conventional models estimate the snow accumulation by applying a temperature threshold and elevation gradient to precipitation measurements. However, such a simplistic representation is a major drawback in current mass balance models and leads to major uncertainties in the results (Machguth et al., 2006, Huss et al. 2014).

We present multi-year measurements of snow accumulation on Findelengletscher (CH) using conventional snow probings and helicopter-borne ground-penetrating radar (GPR). The signal traveltime difference between the snow surface and the snow-ice or snow-firn boundary was converted to depth using a wave velocity estimate based on an empirical relation of the dielectric permittivity with snow density (Sold et al. 2013). For the direct integration in a mass balance model (Huss et al. 2009) the measurements were interpolated to a regular 25m x 25m grid. We applied different interpolation schemes covering the range from simple deterministic methods to geostatistical approaches such as kriging with external drift that incorporates information on the underlying terrain.

The availability of several years of snow accumulation distribution measurements further allows generating a normalised distribution grid that can be used as model input when no or only few direct observations are available. However, the underlying assumption of the involved processes being invariant in time limits the validity of this approach. In order to incorporate processes to a reasonable degree we set up a simple model that accounts for spatial variations in precipitation and wind-dependent redistribution of snow (Helfricht et al. *in press*).

We show that the use of extensive snow accumulation measurements such as by helicopter-borne GPR leads to a substantial improvement of the mass balance model results as indicated by independent validation data that cannot be achieved by sparse conventional measurements. Our data set can further be used to calibrate a simple model for the snow accumulation distribution that yields a considerable improvement compared to conventional accumulation modelling.

REFERENCES

Helfricht, K., Schöber, J., Schneider, K., Sailer, R. & Kuhn, M. in press: Interannual persistence of the seasonal snow cover in a glacierized catchment. Journal of Glaciology.

Huss, M., Bauder, A., & Funk, M. 2009: Homogenization of long-term mass-balance time series. Annals of Glaciology, 50(50), 198-206.

Huss, M., Zemp, M., Joerg, P. C., & Salzmann, N. 2014: High uncertainty in 21st century runoff projections from glacierized basins. Journal of Hydrology, 510, 35–48.

Machguth, H., Eisen, O., Paul, F., & Hoelzle, M. 2006: Strong spatial variability of snow accumulation observed with helicopter-borne GPR on two adjacent Alpine glaciers. Geophysical Research Letters, 33, L13503.

Sold, L., Huss, M., Hoelzle, M., Andereggen, H., Joerg, P. C., & Zemp, M. 2013: Methodological approaches to infer end-of-winter snow distribution on alpine glaciers. Journal of Glaciology, 59(218), 1047–1059.