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13. Cryospheric Sciences

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13. Cryospheric Sciences

Margit Schwikowski, Martin Heggli, Matthias Huss, Jeannette Nötzli, Daniel Tobler, Andreas Vieli

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13.1
Millennial ice record reveals industrial footprint in European vegetation

Sandra O. Brugger [1,2], Erika Gobet [1,2], Christian Rohr [2,3],Federica R. Schanz [1], Fabian Rey [1,2], Christoph Schwörer [1,2], Michael Sigl [2,4], Margit Schwikowski [2,4],[5] & Willy Tinner [1,2]

[1] *Institute of Plant Sciences, University of Bern*
[2] *Oeschger Center for Climate Change Research, University of Bern*
[3] *Institute of History, University of Bern*
[4] *Paul Scherrer Institute, Villigen*
[5] *Department for Chemistry and Biochemistry, University of Bern*

Wild fires are a disturbance agent across the continents, driving ecosystem dynamics and societal hazards. We conducted ice-core palynology using pollen and spores as proxies for vegetation composition and land use activity, microscopic charcoal for fire activity, and spheroidal carbonaceous particles (SCP) for fossil fuel combustion. The results derive from the highest glacier of Europe (4452 m asl), from Colle Gnifetti. To our knowledge they provide the first long-term and high-resolution palynological record of Europe from an ice-core.

The central position and large microfossil catchment of the Colle Gnifetti allows us to address vegetation and societal responses to climatic change and wildfire disturbance on a subcontinental scale, presumably covering substantial parts of Western, Central, and Southern Europe. The ice core record provides an excellent chronological control for the past millennium, particularly over the most recent 200 years, the period that experienced important climatic changes and an increasing globalization of economy.

We reconstruct large scale impacts such as extreme weather, societal innovations, agricultural crises, and pollution in Europe. Surprisingly, pollution tracers occur in the record as early as 1750 AD. They anticipate industrialization in the Alpine region but coincide with a shift to large-scale maize production in Northern Italy and strongly increased fire activity. Our multiproxy record may allow desentagling the role of climate and humans for vegetation composition and biomass burning.

13.2
Mapping and monitoring of Arctic lowland active layer permafrost movement with satellite SAR interferometry

Rafael Caduff [1], Tazio Strozzi [1]

[1] *Gamma Remote Sensing AG, Worbstrasse 225, CH-3073 Gümligen (caduff@gamma-rs.ch)*

Active layer in arctic permafrost lowland regions is expected to increase in extent and thickness with increasing mean annual temperatures. Seasonal thawing and freezing of the uppermost soil layer is considered in most cases for building infrastructures, including transportation ways such as roads or airfields, in arctic regions. However, an increase in active layer thickness and in permafrost thaw activity may shift the stability conditions beyond the structural limit of the infrastructures leading to potential failure. Not only local structural issues may be affected by increased permafrost thaw. The knowledge of the state of permafrost thaw activity outside inhabited areas is crucial as well for the monitoring of the development in greenhouse gas emissions (mainly CO_2 and CH_4) from permafrost soils. A wide area monitoring of the permafrost thaw activity in arctic regions in high temporal and spatial resolution is therefore important for understanding and predicting the role of thawing permafrost for global climatic trends.

We propose a remote-sensing approach for the identification of active layer thawing using satellite radar interferometry (Strozzi et al. 2018). We use the ground motion as proxy since freezing and thawing of the soil leads to volume changes and results in heaving and settling in flat terrain. Differential SAR Interferometry (DInSAR) and persistent scatterer interferometry (PSI) are widely used methods, that allow the precise detection and quantification of ground movements from space. With Sentinel-1 acquisitions regularly available every 6 to 12 days over arctic regions, temporal and spatial patterns of permafrost activity can be monitored on a regular basis even in remote areas.

We will illustrate the general workflow on feasibility studies performed in the Qaanaaq (NW-Greenland) and Ilulissat (W-Greenland) areas using Sentinel-1 data. We will introduce an approach to generate permafrost thaw activity maps from ground motion maps and critically discuss our findings. Open questions such as the influence on the InSAR results of superficial (melt)water, soil moisture changes, and the active layer thickness will be addressed. Finally, an outlook will be given on the use of a standardized permafrost soil activity map as tool for planning and construction works in arctic regions.

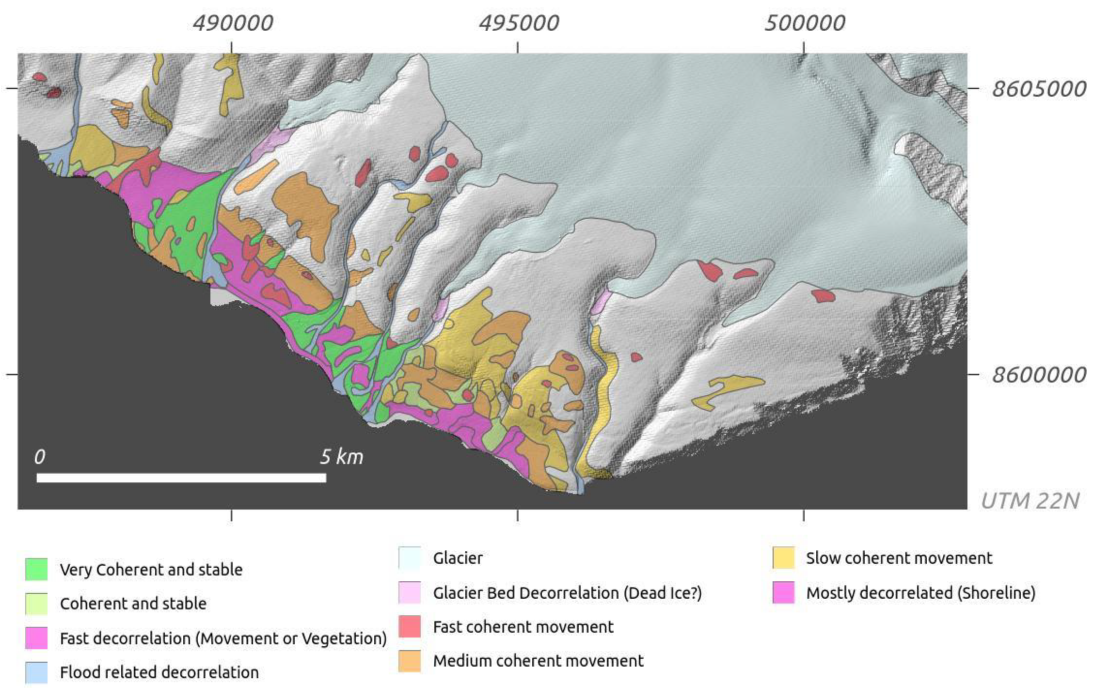

Fig. 1. Map of Sentinel-1 InSAR derived surface movements in the Qaanaaq area (NW-Greenland). Data cover the time between 2015-2018.

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13.3
Investigating the influence of temperature and liquid water on variations in rockglacier flow

Alessandro Cicoira [1], Andreas Vieli [1] and Jérome Faillettaz [1]

[1] *Department of Geography, University of Zurich, Switzerland (alessandro.cicoira@geo.uzh.ch)*

In the past decades, seasonal and inter-annual variability in rockglacier velocities have been observed (Wirz et al., 2016). Temperature forcing along with input of liquid water have been proposed as key processes to explain these variations in kinematics (Ikeda et al, 2008). However, the relative influence of these mechanisms have not yet been quantitatively assessed against real-world data (Kääb et al, 2007). We investigate the processes governing variability in rockglacier flow using 1-dimensional numerical models that couple heat conduction to different creep relations and include variations in pore water pressure (Arenson and Springman, 2005). We compare the modelling with borehole temperatures and surface velocity measurements from several sites of the PERMOS and PermaSense monitoring networks. We find that velocity variations cannot be explained from the influence of temperature forcing on rockglacier rheology alone. Coupling variations in water input to a water pressure dependent creep relation, we are able to reproduce velocity variations both in magnitude and temporal pattern over time scales from several months to several years.

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13.4
Modelling steady states and the transient response of debris-covered glaciers

James Ferguson [1], Andreas Vieli [1]

[1] *Department of Geography, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland (james.ferguson@geo.uzh.ch)*

Debris-covered glaciers are commonly found in alpine landscapes of high relief and increasingly play an important role in a warming climate. When a continuous surface debris layer is thick enough, it reduces the underlying ice ablation rate, which in turn reduces thinning, surface evolution and, therefore, affects the ice dynamics. This results in extended debris-covered glacier tongues with low surface slopes and that are dynamically almost inert. Furthermore, debris-covered glaciers are expected to respond much slower to changes in climate forcing than their debris free counterparts. However, it is not clear whether debris-covered glaciers can have steady states and this affects our ability to better understand the transient response of a debris-covered glacier to climate variations.

In this work, we incorporate a debris source and its transport into a simplified ice flow model. Using both analytical and numerical methods, we explore conditions under which steady states of debris-covered mountain glaciers are possible. We discuss how realistic steady states are by comparing the results to observations and investigate the implications on response times of debris-covered glaciers.

13.5
In-situ Measurements of an Active Seismic Fault at the Bed of an Alpine Glacier

Dominik Gräff [1], Fabian Walter [1], Elisabeth Clyne [2]

[1] *Laboratory for Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Hönggerbergring 26, CH-8093 Zurich (graeff@vaw.baug.ethz.ch)*
[2] *Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA*

Much like for tectonic strike-slip faults in the earth crust, at the bed of glaciers, frictional processes causing seismogenic stick-slip motion exist. While on one hand ice deforms according to a non-linear rheology with a stress dependent viscosity and hence differently from tectonic plates, smooth sliding and stick-slip motion at the interface between glaciers and the underlying bedrock are analogous to creeping and locked sections on tectonic faults.

Until recently, observations of sudden processes at the bed of glaciers were limited to monitoring stick-slip sources form the glacier surface. Here, we show a new approach to study the subglacial environment that was carried out in a field campaign in summer 2018:
By analyzing multi-seasonal recordings from seismometers on the ice in the challenging environment of the ablation zone of four alpine glaciers, the clustering and swarming behavior of basal stick-slip faults was studied in order to determine an optimal site to carry out the first in-situ measurements of an active seismogenic fault at a bi-material interface beneath a glacier. Much like drilling into seismogenic strike-slip faults in crustal studies, enabled by guided fast hot water drilling we target borehole experiments to specific glacier bed regions where spatially limited microseismic stick-slip sliding happens and combine them with the recordings of a high-densitiy network of seismometers at the glacier surface.

From the various measurements we can determine the subglacial water- and thus pore pressure evolution and its effect on the fault stability, while the regular recurrence rate of the microseismic stick-slip events allows to predict both the time and magnitude of the next slip event. Futhermore the in-situ borehole measurements enable us to study material properties such as the till and ice characteristics within the stick-slip asperities and compare them to off-site reference measurements in seimically non-active regions of the glacier bed. Finally from acceleration, ice deformation measurements, and borehole camera videos from the glacier bed, we can estimate the amount of aseismic and co-seismic sliding, which cannot be obtained remotely from the ice surface.

Summed up, with the various in-situ measurements of an seismogenically active strike-slip fault beneath an alpine glacier combined with passive seismic long term monitoring, we open a unique posibility for studying seismogenic stick-slip motion at a bi-material interface in a natural environment.

13.6
Long-term change in ocean heat content using ice core noble gas thermometry

Marcel Haeberli [1], Daniel Baggenstos [1], Jochen Schmitt [1], Thomas Kellerhals [1] & Hubertus Fischer [1]

[1] Physics Institute, Climate and Environmental Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern (haeberli@climate.unibe.ch)

The novel method of ice core noble gas thermometry allows us to reconstruct a global mean ocean temperature (GMOT) on the basis of physical principles.
The xenon/krypton or krypton/N_2 ratio in the atmosphere is a direct proxy for GMOT because of the temperature dependence of their solubility coefficients.

The GMOT, which is the most integrative and representative parameter for quantifying long-term changes in the Earth's energy budget, can be estimated using high-precision measurements of noble gas elemental ratios from gases trapped in glacial ice. Using multi-isotopic gas parameters of N_2, Ar, Kr and Xe, we are able to quantify for dynamics in the firn and ice including fractionation effects (gravitational enrichment, thermodiffusion) as well as for possible gas loss happening in the ice.

We are focusing on peak glacial and interglacial conditions over the last 700'000 years, i.e. covering the last eight glacial and interglacial intervals. The only proxies for ocean temperatures during this time period are sediment cores which have a very strong spatial variability of ocean temperatures between and even within individual basins.

We performed Xe/Kr and Kr/N2 analyses on around 100 ice core samples from EDC and EDML over the last 700 ky. The measurements imply warmer ocean temperature during interglacials and a significantly colder temperature during glacial times. The results are in line with the deep ocean temperature reconstructions from sediment cores.

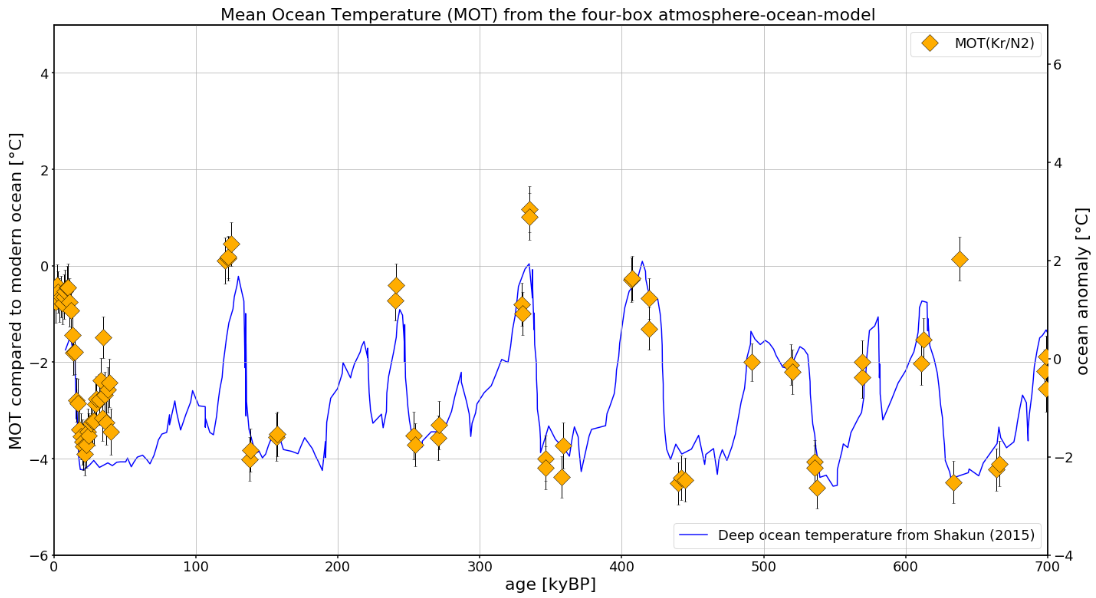

Figure 1. Yellow diamonds are the Global Mean Ocean Temperature (GMOT) records relative to today derived from the atmospheric gas ratio of Kr/N2 using ice core samples from EDC. The blue line is the deep ocean temperature derived from sediment core measurements from Shakun (2015).

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13.7
Comparing shallow and full-Stokes models of the Rhine Glacier during the Last Glacial Maximum

Michael Imhof [1], Denis Cohen [2], Guillaume Jouvet [1], Julien Seguinot [1], Martin Funk [1]

[1] VAW, ETH Zürich, Hönggerbergring 26, CH-8049 Zürich (imhof@vaw.baug.ethz.ch)
[2] Department of Earth and Environmental Science, New Mexico Tech, Socorro, NM, 87801, USA

Paleo ice-sheet models often use simplified stress balances to simulate the ice motion on the time scale of a glacial cycle. For instance, the Parallel Ice Sheet Model (PISM, The PISM authors 2015) has shown a good agreement between modelled and geomorphologically reconstructed ice extent of the European Alpine ice sheet at the Last Glacial Maximum (LGM). However, the modelled maximum ice surface elevation was found up to 800 m higher than the reconstructions based on trimlines (Seguinot et al. 2018). The full-Stokes model Elmer/Ice (Gagliardini et al. 2013) was also applied to the Rhine Glacier at the LGM (Cohen et al. 2018). This offers a unique opportunity to determine the limitations of using a mechanically-simplified model such as PISM to reproduce the ice thickness and dynamics of a former ice field over a complex topography.

For that purpose, we perform an analogous simulation to Cohen et al. (2018) using PISM. We find that the two models -- Elmer/Ice and PISM -- agree well with respect to sliding velocities. However, the shear velocities (surface speed minus sliding speed) modelled by PISM with the Shallow Ice Approximation (SIA) are substantially lower than the ones computed with the full-Stokes model. The reason for this is an artificial ice flux limiter in the SIA in PISM that is used in complex terrain. Allowing less flux limitation results in larger shear velocities -- more similar to Elmer/Ice -- but comes along with increased computational costs. This difficulty of PISM to model the deformation velocities -- especially at high elevation in the accumulation area -- might partly explain the discrepancy in ice surface elevation found in previous studies.

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13.8
Changing firn properties on glaciers in Central Asia

Marlene Kronenberg [1], Horst Machguth [1], Anja Eichler [2,3], Margit Schwikowski [2,3,4] & Martin Hoelzle [1]

[1] *Department of Geosciences, University of Fribourg, Chemin de Musée 4, CH-1700 Fribourg (marlene.kronenberg@unifr.ch)*
[2] *Laboratory of Environmental Chemistry, Paul Scherrer Institute, CH-5232 Villigen*
[3] *Oeschger Centre for Climate Change Research, University of Bern, CH-3012 Bern*
[4] *Department of Chemistry and Biochemistry, University of Bern, CH-3012 Bern*

It has been shown that glacier mass changes in certain areas of Central Asia and neighbouring regions are less negative than the global average. Balanced or even positive mass changes have been identified for glaciers in the Pamir, Karakoram and western Kunlun (e.g. Brun et al., 2017). The reasons for glaciers in these regions being relatively close to equilibrium, however, remain unresolved. In-situ measurements of mass balance and detailed observations especially from the little studied accumulation zones might be the key to detecting and understanding the processes behind the relatively low glacier mass loss or mass gain in these areas.

Here, we focus on two glaciers located in Kyrgyzstan: Gregoriev Ice cap located in the Inner Tien Shan and Abramov Glacier situated in the Pamir Alay (Fig. 1). Abramov Glacier is located close to the regions of low glacier mass loss while Gregoriev is located in an area of pronounced glacier decline. We use snow pits, firn cores and GPR measurements to derive present-day accumulation characteristics, including annual accumulation rates and snow distribution. Furthermore, we compile past accumulation rates for Abramov Glacier based on the exceptionally detailed glacier mass balance monitoring data (1960s to 1990s) (Pertziger, 1996; WGMS, 2015) as well as from ice cores reaching down to the early 1920s (Kislov, 1982). For Gregoriev Ice cap, we use information derived from repeated cores drilled between the 1960s and 2000s (e.g. Thompson et al., 1993) to derive past accumulation rates. First results indicate contrasting firn changes for the two study sites. Data from recently drilled cores show that the firn ice content for Gregoriev Ice cap has increased during the last decades whereas the stratigraphy of Abramov Glacier firn remains relatively similar to the one observed 40 years ago.

Figure 1. Location map of Abramov Glacier and Gregoriev Ice cap.

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13.9
Petrophysical joint inversion of electrical and refraction seismic datasets in alpine permafrost to image ice, water and air contents

Coline Mollaret [1], Florian Wagner [2], Christin Hilbich [1] & Christian Hauck [1]

[1] *Departement of geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg (coline.mollaret@unifr.ch)*
[2] *Department of Geophysics, University of Bonn, Meckenheimer Allee 176, DE-53115 Bonn*

Electrical Resistivity Tomography (ERT) is one of the most commonly used geophysical methods for permafrost monitoring (Hauck & Kneisel, 2008). Ice can be indeed well distinguished from liquid water due to its different electrical properties. However, this method has also limitations as it requires to solve an inverse problem which is usually under-determined and has no unique solution. To reduce the uncertainties and improve the interpretability of the inversion model, geophysical methods are usually combined with ground truth measurements or other geophysical methods. Nevertheless, ice and air are both materials characterized by very high electrical resistivity and are consequently hard to distinguish using ERT alone. Ice can, however, be well distinguished from air from their P-wave velocity properties (3500 m/s vs 330 m/s). Hilbich (2010) showed how refraction seismic monitoring alone can successfully characterize ground ice gain and loss. This is why Refraction Seismic Tomography (RST) is an optimal second geophysical method to be combined with ERT to assess ice or liquid water content and their respective spatio-temporal variabilities.

To fully exploit two geophysical datasets to improve the reliability of the results, several possibilities to combine the independent datasets have been successfully achieved. In this contribution, we jointly invert for the liquid water, ice, air and rock saturations using petrophysical relationships in order to reduce the occurrence of inversion artefacts. A petrophysical joint inversion for the liquid water, ice, air and rock saturations is applied using the general framework for joint inversions provided in pyGIMLI (Rücker et al., 2017). The saturation models are constrained between 0 and 1. The rock content is constrained to be close the a priori estimate prescribed prior to the inversion. In the first instance, several porosity models (homogeneous soil and porosity model derived from boreholes information) are considered as a priori knowledge.

For comparison purposes, we use the petrophysical equations employed by Hauck et al. (2011) in the so-called 4-phase model (4PM), which uses individual ERT and RST inversions and petrophysical relationships to estimate ice, water and air contents. The commonly used Archie's law (Archie, 1942) links the electrical resistivity to the water saturation, while a combination of the equations by Wyllie et al. (1956) and Timur (1968) links the P-wave velocities with the water, ice, air and rock contents.

In a first step, we apply the joint inversion scheme to synthetic datasets, representing different soil types (low/high porosity, low/high ice content), to validate the general applicability of our approach. In a second step, the saturations are jointly inverted from field datasets, which span a large range of conditions from ice-rich permafrost (rock glacier) to ice-poor permafrost sites. Finally, the sensitivities of the different parameters are analysed and the calculated water and ice contents are discussed in relation with the active layer thickness and temperature dataset, when available.

Permanently frozen soils are a very sensitive climate indicator in mountain terrains. Commonly, only soil temperatures are monitored in permafrost research. Indirect geophysical methods are applied to cover a 2nd or 3rd dimension. Jointly interpreting two distinct geophysical datasets is a common procedure for a better ground characterization. Here, we jointly invert the ice water and air saturations from two geophysical datasets to reduce the uncertainties and improve the interpretability of the subsurface. We particularly focus on the individual importance of the parameters on the results and potential improvement of the joint inversion results compared with standard individual inversions.

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13.10
Glacier shrinkage in the Alps continues unabated as revealed by a new glacier inventory from Sentinel 2

Frank Paul [1], Philipp Rastner [1], Roberto Sergio Azzoni [2], Davide Fugazza [3], Raymond Le Bris [1], Johanna Nemec [4], Antoine Rabatel [5], Mélanie Ramusovic [5], Gabriele Schwaizer [4], Claudio Smiraglia [3]

[1] *Department of Geography, University of Zurich, Winterthurerstr. 190, CH-8057 Zurich (frank.paul@geo.uzh.ch)*
[2] *Department of Environmental Science and Policy, University of Milan, Milan, Italy*
[3] *Department of Heart Sciences "Ardito Desio", University of Milan, Milan, Italy*
[4] *ENVEO IT GmbH, Innsbruck, Austria*
[5] *Univ. Grenoble Alpes, CNRS, IRD, Grenoble-INP, Institut des Géosciences de l'Environnement, Grenoble, France*

The on-going glacier shrinkage in the Alps requires frequent updates of glacier outlines to have an accurate database for modelling purposes (e.g. determination of run-off, mass balance, or future glacier extent) and other applications. With the launch of the first Sentinel 2 (S2) satellite in 2015, it became possible to create a consistent, alpine-wide glacier inventory with an unprecedented spatial resolution of 10 m. Fortunately, already the first S2 images acquired in August 2015 provided excellent mapping conditions for about 95% of the glacierized regions in the Alps.

We have used this opportunity to compile a new alpine-wide glacier inventory in a collaborative team effort. In all countries, glacier outlines from the latest national inventories had been used as a guide to compile a consistent update. Cloud cover over some glaciers required including selected Landsat scenes from 2015 and 2016. Due to the intense manual editing required for the numerous debris-covered glaciers, uncertainty was determined by a multiple digitizing experiment with all participants.

Overall, we derived a total glacier area of 1792 km^2 when considering 4260 glaciers >0.02 km^2. This is 14.7% less than the 2100 km^2 derived for the last alpine-wide glacier inventory that was derived from Landsat scenes acquired in 2003, and is equivalent to a mean annual area loss rate of -1.2%. The real loss is even somewhat higher, as the better spatial resolution of S2 allowed us to map glaciers that are not considered in the 2003 inventory, i.e. the 2003 sample is slightly smaller.

13.11
What does ambient seismic noise tell us about glacial crevassing?

Lukas E. Preiswerk [1] & Fabian Walter [1]

[1] *Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zürich, Switzerland, preiswerk@vaw.baug.ethz.ch*

Ambient seismic noise on glaciers is mostly composed of surface waves, which carry information about elastic properties of the ice body through which they pass. Here, we apply this concept to study the ice structure in the uppermost part of a glacier, i.e. the density, depth and orientation of near-surface crevasses. We first analyze data from a temporary seismic array of an Alpine avalanching glaciers in Switzerland, i.e. the hanging glacier in the Eiger-Westflanke, with 3 seismometers (corner frequencies: 1 Hz, array aperture: ~30m, installed for 5 months). There exists a prominent influence of near-surface crevasses on the orientation of the seismic wavefield polarization, and specific resonance frequencies depend on crevasse depths.

In a designated experiment on a small lake-calving glacier near Klausenpass, Switzerland, we apply our results using seismometers operational for a few hours at increasing distances from the calving front. We analyze this dataset with methods established in seismic site characterization, such as spectral ratios and wavefield polarization analysis. Using independent measurements from the "plumb-line system" (Mottram and Benn, 2009), we assess the accuracy of our seismic crevasse-depth measurement method.

Our method aims to monitor glacial crevasses as they grow and become deeper before calving events. Such a monitoring tool would not only improve calving models, but also prove useful for hazard assessment of avalanching glaciers.

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13.12
Quantification of Snow Water Equivalent Using Buried Low Cost GPS Antennas

Ladina Steiner[1], Michael Meindl[1], and Alain Geiger[1]

[1] *Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland (ladinasteiner@ethz.ch)*

Extensive amount of water stored in snow covers has a high impact on flood development during snow melting periods. Early assessment of the snow water equivalent in mountain environments enhance early-warning and thus prevention of major impacts. Sub-snow GNSS techniques are lately suggested to determine liquid water content, snow water equivalent or considered for avalanche rescue. This technique is affordable, flexible, and provides accurate and continuous observations independent on weather conditions.

The potential to quantify snow water equivalent above a GPS antenna placed underneath a snowpack is evaluated using phase based differential GPS processing. Therefore, a measurement network is set-up at the WSL SLF test site “Weissfluhjoch” consisting of a GPS reference station above the snow pack and a low-cost GPS antenna mounted on the ground underneath the snowpack. These measurements are analysed for the winter seasons 2015/16-2017/18. The results are compared to the reference sensors (snow pillow, snow scale, and manual SWE observations) provided by the WSL SLF.

Results of this point-wise estimation of snow water equivalent agree very well with the reference sensors within 5 percent over the three seasons, including the melting periods. Systematic and stochastic effects on the GPS residuals induced by the overlying snowpack could be significantly reduced.

13.13
Analysing calving activity of Eqip Sermia, Greenland, using continuous direct observations

Andrea Walter [1,2], Martin P. Lüthi [1], Andreas Vieli [1]

[1] *Department of Geography, University of Zurich, Winterthurerstr. 190, CH-8057 Zurich (andrea.walter@geo.uzh.ch)*
[2] *ETH Zürich, VAW, Hönggerbergring 26, 8093 Zürich*

Recently, many marine-terminating glaciers of the Greenland ice sheet revealed rapid retreat, thinning and flow acceleration. These glaciers lose about half of their mass by calving, a process which can change on short timescales. Despite their importance for global sea level rise, major limitations in understanding the dynamics of these glaciers remain. To overcome such limitations, especially detailed observational data is needed.

We observed an outlet glacier in West-Greenland during an eight-day field campaign in 2018 by using a terrestrial radar interferometer, pressure sensors and a time-lapse camera. A combination of these technologies provides us with displacement and topographical data with a spatial resolution of 5 meters in one minute intervals, water height data with a temporal resolution of 2 seconds and images of the glacier front every 10 seconds. This continuous very detailed dataset enables us to get new insights of the calving process. We use these data to establish detailed calving event statistics which are compared to environmental forcing like tides or weather conditions. By identifying source areas and ice volumes of individual calving events we quantitatively investigate the relationship between calving front geometry, calving rate and potential drivers. Additionally, the comparison between the individual datasets allows us to link the shape of tsunami wave oscillations to different calving types and event volumes. Therefore, we can extend the individual calving event statistics from short timescale to long timescale over 5 years.

13.14
Assessing the influence of convection in the active layer of a rock glacier on ground temperatures

Jonas Wicky [1], Christian Hauck [1]

[1] *Alpine Cryosphere and Geomorphology Group, Unit of Geography, Department of Geosciences, University of Fribourg, Chemin du Musée 4, 1700 Fribourg (jonas.wicky@unifr.ch)*

In the Swiss Alps permafrost is a widespread phenomenon with a great impact on the landscape particularly regarding natural hazards. Permafrost occurrence is not only influenced by meteorological parameters and the elevation of the site, also landform and subsurface substrate have a significant impact on the ground thermal regime. Mountain permafrost is often covered by coarse blocky material with a high permeability which allows air to circulate within the ground. Thus, convective heat transfer takes place and influences the ground temperatures.

Numerical modelling approaches in mountain permafrost often either neglect or parametrize ground convection (e.g., Pruessner et al. 2018, Luethi et al. 2017, Scherler et al. 2014). Explicit modelling approaches are rare. In a previous study we successfully modelled the influence of convection on the thermal regime of an Alpine talus slope (Wicky & Hauck, 2017). In this study, we present results from numerical experiments on the effect of air circulation within the porous active layer of an Alpine rock glacier. The model solves for air flow coupled with heat transfer on a 2D domain and is setup within COMSOL Multiphysics. We use data for forcing and validation from the Murtèl rock glacier in the Engadin (Eastern Swiss Alps) provided by the Swiss permafrost monitoring network (PERMOS, 2016).

The model results show that convective heat transfer in the active layer has a significant effect on the thermal regime of a rock glacier. Winter temperatures are highly influenced by convective heat transfer due to the unstable thermal stratification of the air which allows a pronounced convective cooling, whereas summer temperatures show almost no sensitivity to convective heat transfer. Wintertime air circulation is characterized by vertical multicellular convection. During summer a gentle down flow of air takes place (Fig. 1). The prevailing air circulation pattern and the efficiency of cooling strongly depend on the thermal gradient between ground and atmosphere temperatures as well as on the material properties. Especially the permeability of the porous active layer plays an important role.

Compared to borehole data, the model performs well but shows some discrepancy at depth, which is maybe due to convection within the rock glacier body (ice core) which is not represented so far and uncertainties in the material properties, especially regarding the permeability. Our results highlight that air convection cannot be neglected in porous permafrost substrate and should be considered in future modelling approaches. Under warming climate conditions and increased permafrost thaw a proper understanding of the ground thermal regime is crucial to model reliable future projections.

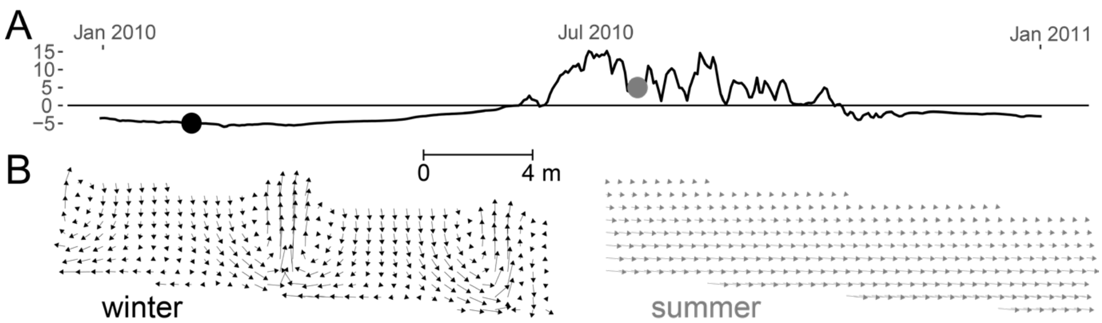

Figure 1. (A) Boundary temperature from the uppermost thermistor at Murtèl borehole COR_0287 (PERMOS, 2016) with a black (grey) dot indicating the time of the circulation snapshot B. (B) Typical circulation patterns within the active layer of a rock glacier. Wintertime multicellular convection (left) and summertime down flow (right).

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13.15
Modelling the evolution of Alpine glaciers under the EURO-CORDEX RCM ensemble

Harry Zekollari [1,2], Matthias Huss [1,3], Daniel Farinotti [1,2]

[1] Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, Zürich, Switzerland (zharry@ethz.ch)
[2] Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland
[3] Department of Geosciences, University of Fribourg, Fribourg, Switzerland

The retreat of the ca. 3500 glaciers in the European Alps has severe implications for the availability of water resources, natural hazards, and the perception of mountains as a recreational environment. To date, studies on the future evolution of glaciers typically rely on parameterizations, in which ice dynamics are not explicitly accounted for. So far, only few studies have explicitly coupled ice flow and surface mass balance processes, and these have mostly focused on individual glaciers, rather than regional scales.

Here, we model the 1990-2100 evolution of all glaciers in the European Alps accounting for both surface mass balance and ice dynamic processes. For doing so, we include an ice flow component into the Global Glacier Evolution Model (GloGEM). Glacier outlines from the Randolph Glacier Inventory are utilized, while an inversion approach is used to estimate the initial glacier thickness. For model validation and calibration, we rely on a vast dataset, including in-situ and geodetic mass balance measurements, glacier length changes, and surface velocity measurements amongst others. This allows for a novel, glacier-specific calibration procedure. The climatic data for the validation and the historical period is drawn from the ENSEMBLES daily gridded observational dataset (E-OBS v.17.0), while for future climatic conditions we rely on EURO-CORDEX Regional Climate Model simulations.

Under a RCP2.6 scenario, the glacier volume loss projected for the end of the century (ca. 60% against a 2003 baseline), is lower than most previous estimates that did not account for ice flow explicitly. Under a RCP8.5 scenario, instead, future glacier evolution is dictated by increased surface melt, reducing the importance of ice dynamics effects. Under such a scenario, Alpine glaciers are projected to largely disappear by the end of the century, with a volume and area loss of 90-95% and around 90%, respectively.

P 13.1
Seasonal evolution of englacial conduits through repeated ground penetrating radar measurements

Gregory Church [1], Andreas Bauder [1], Hansruedi Maurer [2]

[1] Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, Hönggerbergring 26, CH-8093 Zürich (church@vaw.baug.ethz.ch)
[2] Department of Earth Sciences, Institute of Geophysics ETH Zürich, Zürich, Switzerland

Englacial and subglacial meltwater conduits are constantly evolving throughout the season on temperate glaciers, and they strongly influence glacier dynamics and the catchment hydrology. Additionally, it is important to monitor these englacial systems for natural hazard management.

Here, we present a study conducted on Rhone Glacier, Switzerland. This is a temperate glacier located in the central Swiss Alps (Figure 1, left) flowing in a southerly direction from an altitude of 3600 m down to 2200 m. Since 1878 the glacier has retreated 1700 m exposing a granite bedrock and a proglacial lake formed in 2005 due to the excessive retreating.

We have monitored the englacial drainage system in the lower ablation zone throughout the 2018 season using a PulseEkko 25MHz ground-penetrating radar (GPR) system. GPR is highly sensitive to the presence of water and is therefore a suitable tool to monitor englacial conduit evolution.

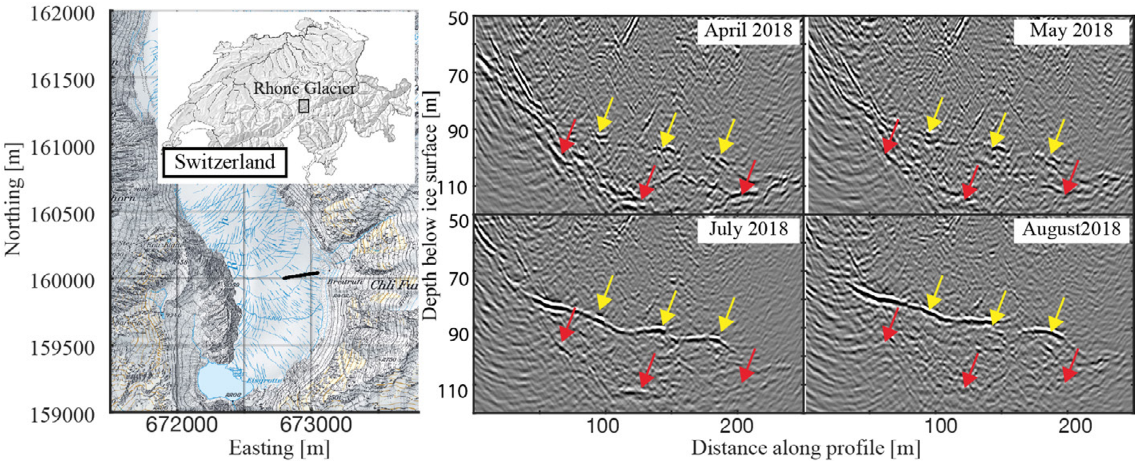

Figure 1. Left: Location map of Rhone glacier and surface-based GPR location shown in black. Right: Ground-penetrating radar sections over an englacial conduit (yellow arrows) and bedrock (red arrows) for different months throughout 2018.

The GPR results (Figure 1, right) show an englacial network developing over a season. Analysis of the englacial GPR reflection strength indicated the hydrological conduit conditions. Weak GPR reflection amplitude at the beginning of the year indicated dry conditions with a small quantity of debris-rich ice. In contrast, strong GPR reflection amplitudes in July and August indicated free water within the englacial conduit. These observations were confirmed by a borehole drilling campaign and the use of a borehole camera in August 2018 to identify the reflection origin. The source of the englacial meltwater conduits is fed from the numerous runoff streams on the eastern moraine. These streams run subglacially alongside the glacier flank and become englacial conduits at 80 m below the ice surface potentially flowing through cracks and crevasses.

Temporal changes that were detected from the repeated GPR surveys indicate that a temperate glacier exhibits strong seasonal changes in hydrological conditions. We have been able to monitor these temporal changes remotely with GPR and with additional in-situ borehole observations.

P 13.2
Crystal orientation fabric analysis on ice core samples from a temperate Alpine glacier

Sebastian Hellmann [1,2], Andreas Bauder [1], Johanna Kerch [3], Hansruedi Maurer [2]

[1] *Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich, Hönggerbergring 26, CH-8092 Zürich (sebastian.hellmann@erdw.ethz.ch)*
[2] *Institute of Geophysics, ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich*
[3] *Alfred-Wegener-Institute for Polar and Marine Research, Am alten Hafen 26, D-27568 Bremerhaven*

Ice under natural conditions shows a typical hexagonal crystal structure with an optical axis perpendicular to the basal planes often referred to as c-axis (Cuffey&Patterson, 2010). In the direction of the c-axis the crystal is significantly harder under pressure compared to the other directions.
Polar ice cores or cores from cold alpine ice have been analysed extensively in recent years (Montagnat et al., 2014; Weikusat et al., 2017; Kerch et al., 2018) showing a direct relationship between the stress regime and the crystal orientation. Furthermore, cystal orientation fabric (COF) was found to affect geophysical measurements such as acoustics and ground-penetrating radar by introducing an anisotropy effect (Diez et al. 2014).

Our investigations are focussed on the ablation zone of Rhone Glacier. Using geophysical experiments in a ring of 12 boreholes we try to detect crystal anisotropy effects in acoustic waves also for those shallow temperate glaciers. These finding are compared with an 80 m long ice core drilled in the center of the ring in summer 2017. Due to the specific technique (Schwikowski et al., 2014), the orientation of the ice core relative to the direction of glacier flow could be preserved, thereby allowing a direct comparison with the geophysical measurements from different azimuth angles.
The COF of the ice core was analysed for 7 different depths along the ice core using the G50 fabric analyser at Alfred-Wegener-Institute in Bremerhaven, Germany. 9-12 ice core thin sections with a diameter of 6-8 cm in 3 perpendicular directions were prepared due to a relatively large grain size of several centimeters to measure a reasonable amount of crystals in each depth for the statistical evaluation.

Figure 1 shows the detected c-axis orientations along the profile. In the upper part of the glacier a mainly vertically oriented COF could be identified. This pattern changes with increasing depth towards a more horizontal COF. However, the analysis of the ice core data has to be improved. Detailed analyses showed that several small grains were probably formed due to recrystallisation after ice core retrieving or could have been melt water veins that randomly refroze during storage. Those particular crystals may lead to a miss-interpretation. Therefore the grain size needs to be considered when analysing the images of the thin sections.
We present the method and results of our ice core analysis and compare these findings with our acoustic measurements in context of a potential anisotropy effect visible in travel times of elastic waves. Our study contributes to a better understanding of crystal anisotropy in temperate glacier ice and links between glaciological and geophysical methods.

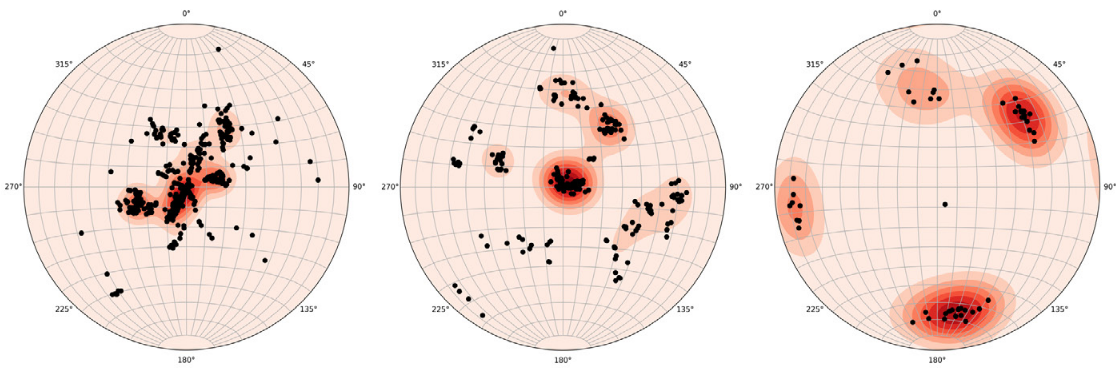

Figure 1. COF analysis in different depths (2 m, 52 m, 79 m below surface) of an ice core from Rhone Glacier, Central Swiss Alps showing an transition from mainly vertically oriented ice crystals towards more horizontal distribution with increasing depth.

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P 13.3
Locating and monitoring glaciohydraulic tremors on Glacier de la Plaine Morte, Switzerland

Fabian Lindner [1], Fabian Walter [1] & Gabi Laske [2]

[1] *Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zürich, Hönggerbergring 26, CH-8093 Zürich (lindner@vaw.baug.ethz.ch)*
[2] *Scripps Institution of Oceanography, UC San Diego, USA*

In glaciated regions where temperatures allow melting, the resulting surface runoff is routed through and beneath glaciers. In case the water supply overwhelms the capacity of the subglacial conduits, the water pressure at the glacier's base is increased. This pressure increase promotes basal motion, hence, glacial hydraulics influences ice flow. On its passage through and beneath the glacier, the water interacts with the ice walls due to turbulent flow or excitation of resonances in the conduits. These processes act as seismic sources emitting waves which – given the wave generation is sufficiently strong – can be recorded at the glacier's surface as continuous seismic tremors (Bartholomaus et al., 2015; Gimbert et al., 2016; Roeoesli et al., 2016). We attempt to locate such tremors observed on Glacier de la Plaine Morte in summer 2016 and investigate the time evolution of their source locations. Our data include the signal from the drainage of an ice-dammed lake which resulted in a sudden perturbation of the subglacial drainage system. We apply a classic array processing technique to measure the source direction as observed in different parts of the glacier. These measurements are combined with a more holistic approach using the seismic recordings from different parts of the glacier simultaneously. We identify times where tremors are generated in moulins. Furthermore, analysis of the background signal suggests that it is generated in a channel-like structure close to the glacier terminus. These results show that surface seismic measurements allow insights into the subglacial drainage system – an otherwise hard-to-access environment.

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P 13.4
Long-term multi-resolution terrestrial photogrammetry at the Moosfluh landslide

Fabian Neyer[1], Sébastien Guillaume[1], Philippe Limpach[2] & Alain Geiger[1]

[1] *Institute of Geodesy and Photogrammetry, ETH Zurich, 8093 Zurich, Switzerland (fabian.neyer@geod.baug.ethz.ch)*
[2] *BSF Swissphoto, Dorfstrasse 53, CH-8105 Regensdorf-Watt*

Risks and hazard analyses of potential environmental mass movements are typically based on geodetic measurements (GPS, total station, laser, radar, imagery, etc.) or qualitative interpretation by experts. Each methodology has its strengths and weaknesses, whereas the ultimate goal is to combine the various techniques to obtain an undisturbed picture of the scene with high confidence. This work focuses on the combination of high-precision GPS and image-based estimates using permanent multi-resolution online camera systems.

Our monitoring system was installed in the Aletsch area, focusing on the Moosfluh landslide. While permanent GPS stations are within the landslide area, three permanent camera systems are mounted on stable rock on the opposite side of the valley. There are currently two online and real-time GPS stations on the landslide that can be identified in the images. Image coordinates of the GPS antenna centers are linked to their estimated coordinates and thus serve as an absolute references. To increase the network of known coordinates, additional ground control points were measured and assigned in the image spaces using QDeadalus (Guillaume et al., 2016). QDeadalus is a total station equipped with a video camera with a small field of view. About 20 natural landmarks were measured from two different viewpoints at distances between 1.5 and 3.5 kilometers. The additional natural control points could be measured to an accuracy of a few centimeters and were subsequently included in the self-calibrating photogrammetric bundle adjustment of the network. GPS was also used to estimate accurate camera position coordinates. Fixing the station coordinates improves the 3-dimensional reconstruction accuracy significantly (Neyer, 2016), thus camera positions were fixed in the subsequent adjustments.

All cameras are synchronized to the level of a few seconds such that synchronized multi-view time lapse of images results. For each epoch, a set of points (tie points) is determined and matched across the different views. The same tie points are also tracked across the different epochs such that for each feature, a 3-dimensional trajectory can be estimated. Due to the nature of the creep phenomena, some rock boulders experience - despite obvious translations - also large rotations. For a successful match in the image spaces through time, we estimate the parameters of local similarity transformations by the principles of least-squares image matching.

Two of the three permanent camera stations are dual camera systems, i.e., an overview and a zoom camera with a smaller field of view. The latter focuses on an area of interest that is also visible in the overview camera. Features detected in the zoom image are mapped into the coordinate system of the overview camera with a precision of about 0.02 pixels. Apart from logistical advantages, this also allows to use the high resolution images for a more accurate feature selection while not having more station parameters to solve in the adjustment. As a result, object coordinates identified in the zoom images show smaller standard deviations, i.e., they are approximately proportional to the ratio of the different focal lengths between the zoom and the overview cameras.

A network with three camera stations is usually a weak photogrammetric network, i.e., the robustness and reliability are low. While object point accuracies are in the order of 1 to 0.5 pixels (when back-projected), the accurate identification of features across multiple views is currently the limitation of the method. Presently we use SURF descriptors and manual identification for matching across the views. Alternatively, least-squares matching could be performed but it becomes difficulty or inaccurate when features are seen from angular separations larger than about 20 degrees (which the case here). Nevertheless, the proposed processing pipeline delivers direct 3-dimensional rock trajectories at an error level of a few centimeters in the area of interest.

Here we give insights into the applied measuring and processing techniques of this project, illustrate its potentials and limitations, as well as showing results obtained so far.

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P 13.5
A more than 100 years time series of seasonal mass balance for Golubin Glacier, Northern Tien Shan

Erlan Azisov [1], Martina Barandun [2], Martin Hoelzle [2], Marlene Kronenberg [2], Tomas Saks [2], Sergiy Vorogushyn [3] & Ryskul Usubaliev [1]

[1] Central Asian Institute for Applied Geosciences, Timur Frunse Street 73/2, KG-720072 Bishkek (e.azisov@caiag.kg)
[2] Department of Geosciences, University of Fribourg, CH-1700 Fribourg
[3] German Research Center for Geosciences, DE-Potsdam

Golubin is a mountain glacier (Figure 1) with an area of 5.5 km^2 (in 2002) and spans an elevation range from 3300 to 4400 m a.s.l. The glacier is located in the Ala-Archa catchment, in the Kyrgyz Ala-Too range, northern Tien Shan. Mass balance of Golubin Glacier was measured by the glaciological method from 1969 to 1994 and regular annual measurements have been reinitiated in 2010. In 2013, an automamtic weather station and an automatic camera for transient snow line observations have been installed in the vicinity of the glacier. Furthermore, precipitation and temperature data are available from Alplager weather station located at 2340 m a.s.l. since 1980. In addition to these insitu data, complimentary information on glacier mass and area changes can be obtained from remote sensing data and reanalysis data can be used to extend the precipitation and temperature time series.

In this study, we combine different data sets and methods to derive a centennial time series of seasonal glacier mass balance of Golubin Glacier. In a first step (i), we calibrate a mass balance model (Huss, 2009) with annual mass balance measured for 2010-17. The model is forced with data from Alplager station. In the following, (ii) we apply the calibrated model to calculate the mass balance back to 1980. (iii) The modelled mass balance is evaluated against historic mass balance measurements. As a next step, (iv) the model is run with Reanalysis data reaching back to 1901 and the model calibration steps were repeated. The therefrom obtained cumulative mass balances are validated against published geodetic mass balances of the glacier (e.g. Bolch 2015) and against secular glacier mass balances derived from length changes following the approach of Hoelzle (2003).

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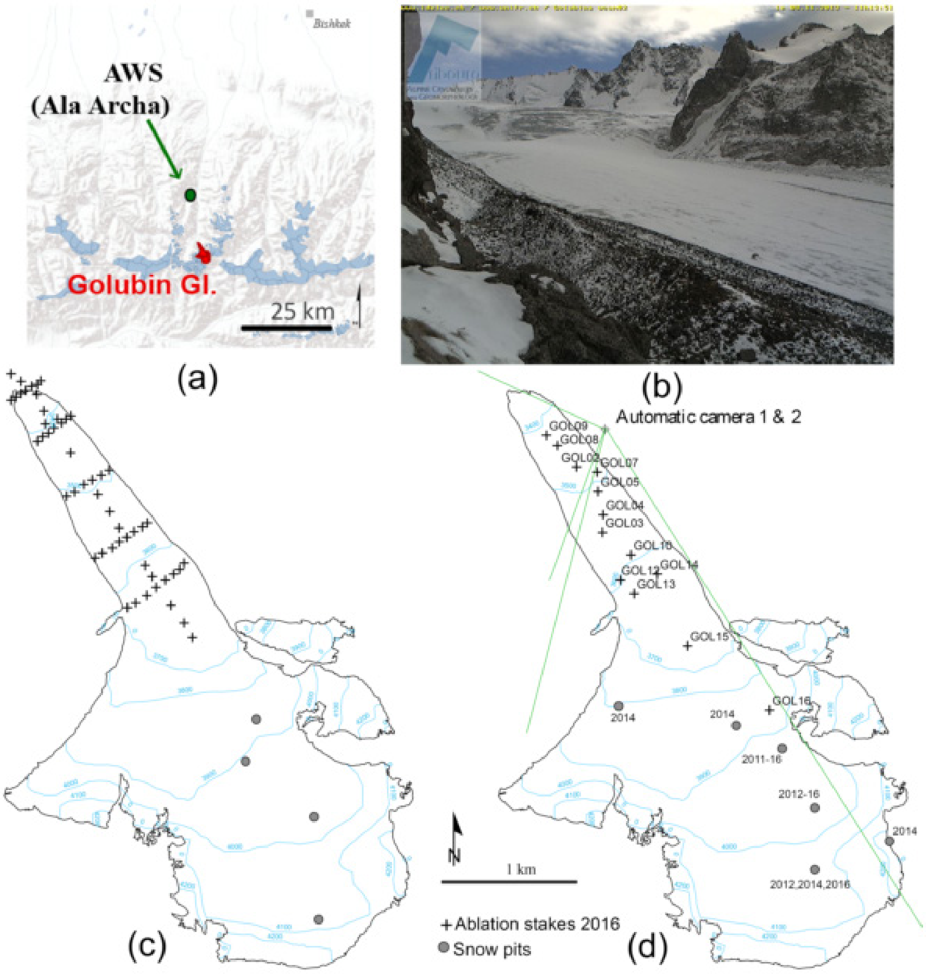

Figure 1. From Hoelzle et al. (2017). Historical (c) and new (d) mass balance network on the Golubin Glacier (Kyrgyzstan) with corresponding (overview) map (a) and snow line camera picture (b).

P 13.6
Mass balance monitoring and capacity building in Central Asia

Alyssa Ghirlanda [1], Marlene Kronenberg [1], Martina Barandun [1], Erlan Azisov [2], Abdulhamid Kayumov [3], Ruslan Kenzehbaev [2], Horst Machguth [1], Tomas Saks [1], Yura Tarasov [4], Ryskul Usubaliev [2], Andrey Yakovlev [5], Martin Hoelzle [1]

[1] Department of Geosciences, University of Fribourg, Switzerland (alyssa.ghirlanda@unifr.ch)
[2] Central Asian Institute for Applied Geosciences, Bishkek, Kyrgyzstan
[3] Institute of Water Problems, Hydro-Power Engineering and Ecology, Dushambe, Tajikistan
[4] UZHydromet, Tashkent, Uzbekistan
[5] Uzbek scientific investigation and design survey institute, UzGIP, Tashkent, Uzbekistan

Glaciers are a key component of the high-mountain environment in Central Asia. They are essential for water availability in the arid and intensely populated areas located downstream. Moreover, glacier retreat can trigger natural hazards, such as glacier lake outburst floods (GLOFs). However, in Central Asia, glacier mass balance observations, which are required for efficient water management and disaster risk reduction, are sparse and often discontinuous.

According to regional mass balance studies based on remote sensing data, glaciers in the Tien Shan are characterised by substantial mass loss during the last decades. As for glaciers located in the neighbouring Pamir Mountains, several geodetic mass balance studies suggest less negative mass balances or balanced conditions. However, changing processes cannot be fully understood based on remote sensing studies only. Such studies often rely on bulk estimates, provide only semi-decadal to decadal changes and are connected to uncertainties which are challenging to quantify. Therefore, a combination of approaches is necessary to reduce uncertainties. A promising approach, where observations of remotely sensed transient snowlines and geodetic mass balances are used to constrain a simple mass balance model, provides annual mass balance series for remote and inaccessible glaciers. Nevertheless, in-situ measurements of glacier mass balance are still a prerequisite for validation and calibration of any combined remote sensing/modelling approach.

On the one hand, extensive mass balance monitoring programmes are needed to overcome the data scarcity in Central Asia. On the other hand, capacity-building efforts in the research area of the fast changing cryosphere are necessary to ensure the sustainability of monitoring activities. Furthermore, from a societal perspective, capacity building needs to address related domains of Water Resource Management and Disaster Risk Reduction.

The project Cryospheric Climate Services for improved Adaption (CICADA) aims on a capacity building in the above-mentioned domains amongst stakeholders in Central Asia and the continuous monitoring and open access of in situ data from glaciers in this data sparse region. Here, we give an overview of the CICADA project and an insight into different mass balance studies of Central Asian Glaciers performed within CICADA and related projects.

P 13.7
Ice volume estimation in the Swiss Alps from helicopter-borne GPR and glaciological modeling

Melchior Grab [1,2], Lisbeth Langhammer [1], Andreas Bauder [2], Lasse Rabenstein [3], Lino Schmid [1,2] & Hansruedi Maurer [1]

[1] Institute for Geophysics, ETH Zurich, Sonneggstrasse 5, 8092 Zürich (melchior.grab@erdw.ethz.ch)
[2] Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich, Hönggerbergring 26, 8092 Zürich
[3] Drift & Noise Polar Services GmbH, Hohenlohestr 8, 28209 Bremen

For overcoming future challenges arising from the ongoing melting of glaciers, an accurate prediction of the future river discharge and the topography of deglaciating regions is needed. A good knowledge of the current ice thickness distribution builds the basis for such predictions. To obtain this information for the glaciers in Switzerland, we have developed a helicopter-borne ground penetrating radar (GPR)-instrument from commercially available components (Langhammer et al., 2017) and a MATLAB®-based data processing software package (Grab et al. 2018).

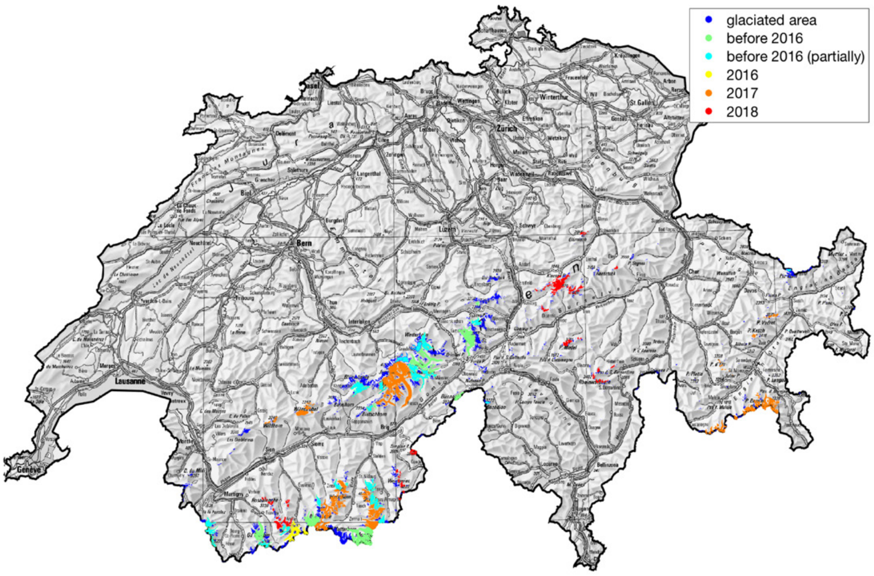

Figure 1: Current status (by August 2018) of the data acquisition. Glaciers are color-coded to show the year of data acquisition (green, yellow, orange, and red). Glaciers only partially surveyed are shown in light blue.

During the past years, the GPR-instrument has been used for recording data from numerous glaciers in the Swiss Alps. To date, a total of around 1’000 km of GPR-profiles has been recorded with the new instrument. Together with data recorded at earlier years (1999-2015, around 1’400 km), a large data base has been built, which includes data for most glaciated regions in Switzerland (Fig. 1).

The GPR data provide the ice thickness and the topography of the bedrock on a sparse grid across the glaciers. We combine these data with glaciological modeling techniques, in order to estimate the total ice volume and to provide continuous ice thickness maps and bedrock topography maps. Therefore, we have developed the **Gla**cier **T**hickness **E**stimation (**GlaTE**) algorithm. It allows to adequately invert for the three-dimensional ice thickness of Alpine glaciers based on glaciological modeling (after Clarke et al., 2013) and observable data constraints (glacier outlines, digital elevation model, and GPR data). An example result is shown in Fig. 2 for the Morteratsch glacier, computed by L. Langhammer (2018).

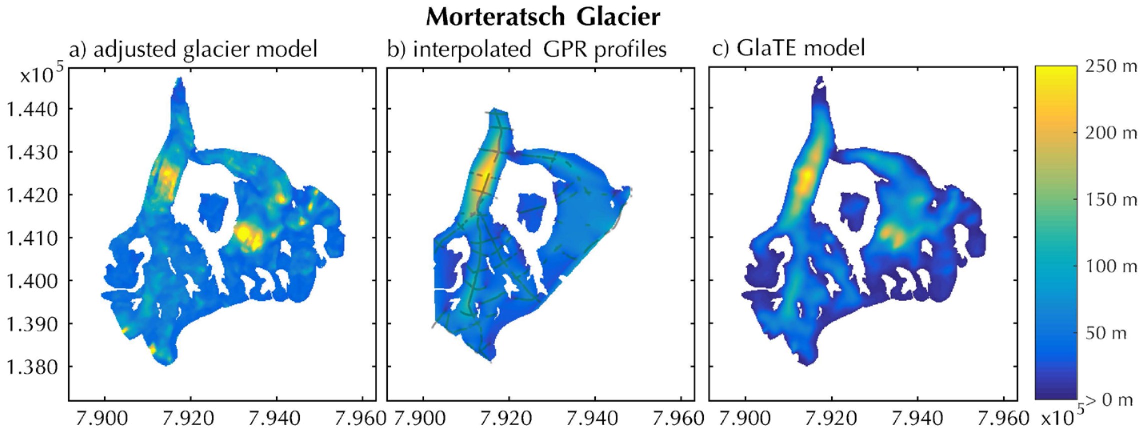

Figure 2: Ice thickness estimation of the Morteratsch Glacier: Computed by L. Langhammer (2018) using (a) the glaciological model after Clarke et al. (2013), (b) interpolation of GPR data, and (c) the GlaTE algorithm.

In the framework of the Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE), it is our aim to soon provide an update about the total ice volume in the Swiss Alps. The processing of the recorded GPR data is already finished and we currently work on the finalization of the interpretation of the numerous GPR profiles. Furthermore, some more measuring campaigns are planned to fill the data gabs (blue and light blue regions in Fig. 1) with the primary focus on the larger glaciers.

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P 13.8
The potential of low-cost UAVs and open-source photogrammetry software for high-resolution glacier monitoring – A case study from the Kanderfirn (Swiss Alps)

Alexander Raphael Groos [1], Lukas Munz [1], Thalia Bertschinger [1]

[1] *Institute of Geography, University of Bern, Hallerstrasse 12, CH-3012 Bern (alexander.groos@giub.unibe.ch)*

Unmanned Aerial Vehicles (UAVs) represent a relatively new, but powerful, tool in the field of glaciology and are mainly used in combination with proprietary photogrammetry software to obtain high-resolution glacier surface information (e.g. Bhardwaj et al. 2016). As a free and low-cost alternative, self-developed fixed-wing UAVs equipped with optical instruments were tested for high-resolution monitoring of the Kanderfirn glacier in the Swiss Alps during summer 2017 and 2018. The taken aerial photographs were postprocessed in the open-source photogrammetry software OpenDroneMap to generate othophotos and digital surface models. Based on the comparison of the consecutive overflights, velocities, surface height changes, ablation, surface roughness etc. were calculated. The preliminery results demonstrate that low-cost UAVs in combination with open-source software are an affordable alternative to commercial remote sensing platforms and have the potential to deliver geo-data in high spatial and temporal resolution required for the investigation of glacier dynamics as well as the validation of model results and satellite products.

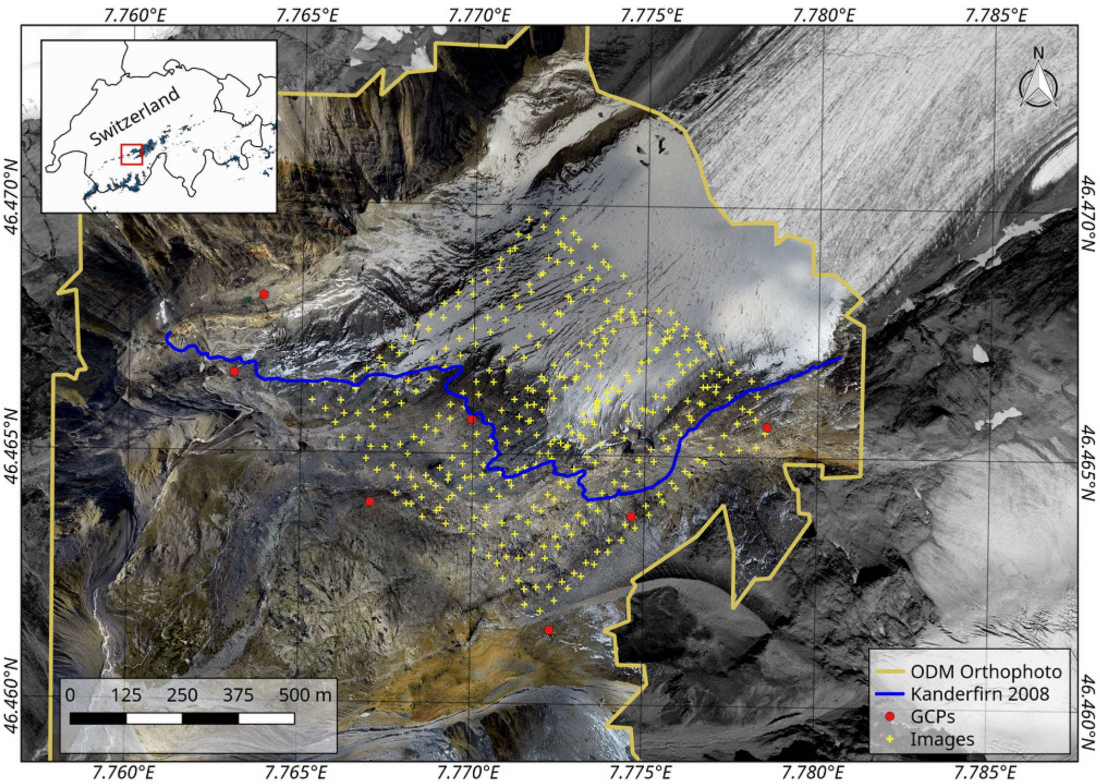

Figure 1. High-resolution orthophoto (pixel size: 5 x 5 cm) of the tongue of the Kanderfirn glacier (Swiss Alps) obtained from 393 UAV images using the photogrammetry software OpenDroneMap. An airborne orthophoto from the year 2008, provided by SwissTopo, is displayed in the background.

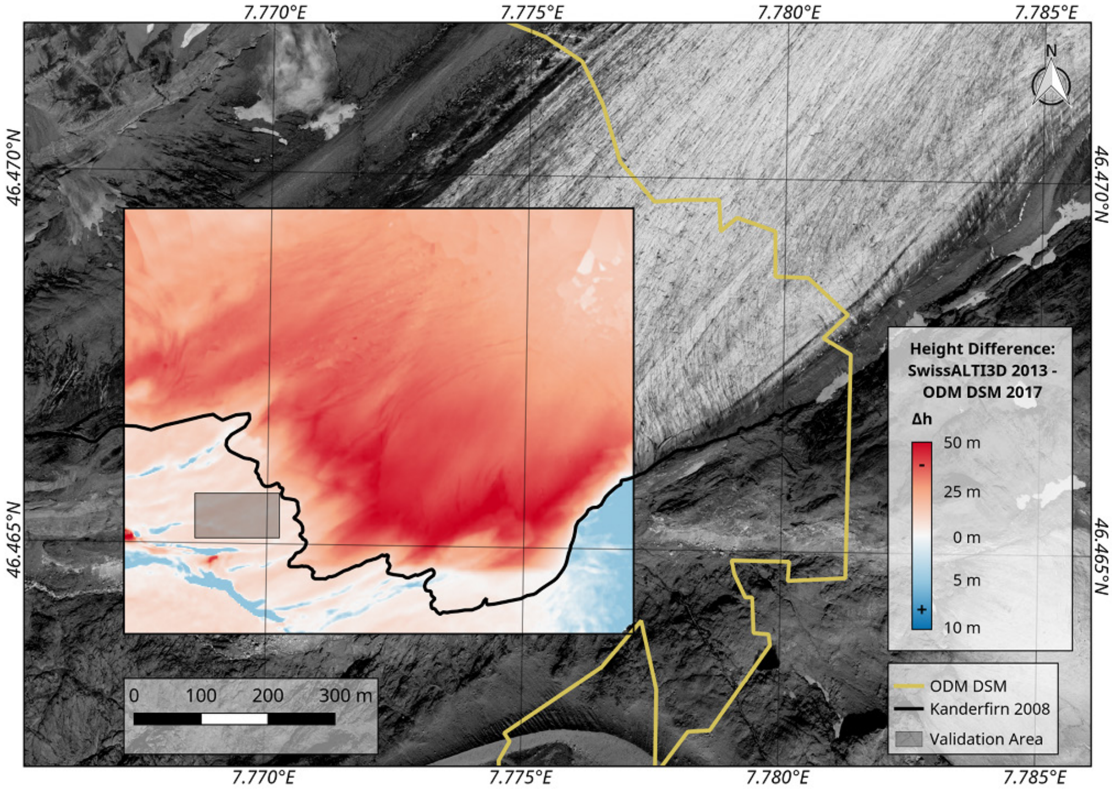

Figure 2. Elevation change at the tongue of the Kanderfirn glacier between summer 2011 and 2017 derived from the comparison of the SwissALTI3D Digital Surface Model (DSM), provided by SwissTopo, and the OpenDroneMap DSM obtained from UAV imagery.

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P 13.9
Calorimetric determination of the unfrozen water content in glacier ice

Martin Lüthi [1]

[1] *Geogrphical Institute, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich (martin.luethi@geo.uzh.ch)*

Glacier ice at the melting temperature may contain up to 6% of unfrozen water, as was inferred with indirect methods such as ice-penetrating radar. This inter-grain water influences ice deformation, the thermal structure of ice sheets, and subglacial hydrology.

We determined by the content of free water in-situ in ice tunnels of serveral temperate glaciers. The calorimeter consists of an active cooling system in a central borehole and a set of thermistors which are placed in several distances from the center. We thus measure the velocity of the freezing front as well as the cooling rates. With help of a 3D finite element heat flow model synthetic freezing curves are obtained for various initial water contents. Matching these synthetic curves to the measurements yields in-situ water contents between 0 and about 3% in basal ice. These values confirm the indirectly derived free water contents.

P 13.10
Inverting debris thickness on glaciers from UAV thermal imagery

Martin Schulthess [1], Nico Mölg [1], Andreas Vieli [1]

[1] *Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zürich (martin.ch.schulthess@bluewin.ch)*

The thickness of debris cover on glaciers is strongly affecting the rate of ablation and thereby changes the response in mass loss and flow dynamics of debris-covered glaciers in context of climate forcing. For example, only 6 cm of debris can reduce ablation by about a factor of two; thus, the debris thickness and its spatial distribution over the glacier tongue are crucial for estimating and predicting ablation, and consequently the mass balance and evolution of such glaciers.

On the example of the debris-covered tongue of Zmuttgletscher (Swiss Alps), we explore the capability of using thermal imagery from a UAV to derive high-resolution distribution maps of debris thickness on glaciers. Using aerial infra-red images from a fixed-wing UAV equipped with a thermal camera and Structure-from-Motion methods, we are able to derive a thermal orthophoto of surface temperatures for the debris-covered tongue of Zmuttgletscher. The surface-temperature image is corrected for calibration-offsets using melt-patches (0 °C) and in-situ surface measurements. Using the UAV-derived surface temperatures and DEM and additional data from an in-situ meteo-station and considering the energy fluxes within the debris under the simplification of assuming a linear average debris temperature gradient, we invert for the debris thickness. We then assess the produced debris thickness map with in-situ debris thickness measurements.

We find very high spatial variability in surface temperatures and hence debris thicknesses for thicknesses below about 12cm. Above this threshold debris-thickness variations are difficult to derive from thermal imagery, but they also do no longer substantially change the sub-debris melt rates, as they are already strongly reduced.

We further find that the time during the day of acquisition of the thermal images is affecting the debris-thickness inversion results and that a fully time-dependent consideration of energy fluxes would likely be beneficial.

P 13.11
Monitoring and modeling a recurrent calving event at Bowdoin Glacier, Greenland

Eef van Dongen [1], Andrea Walter [2], Guillaume Jouvet [1], Daniel Farinotti [1,3], Martin Funk [1]

[1] *Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, CH-8093 Zürich (vandongen@vaw.baug.ethz.ch)*
[2] *Department of Geography, University of Zurich, CH-8057 Zürich*
[3] *Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), CH-8903 Birmensdorf*

The thinning and retreat of ocean-terminating, calving glaciers worldwide has contributed substantially to sea-level rise over the last decades. The size and the frequency of calving events may vary by several orders of magnitude. At Bowdoin Glacier, Northwest Greenland, most of the yearly mass loss by calving is due to a few large events (Jouvet 2017). Here, we analyse two relatively large-scale calving events in detail, which occurred nearly at the same location on Bowdoin Glacier and followed a very similar fracturing pattern. Our analysis relies on data obtained by interferometric radar and UAV photogrammetry during two summer fieldwork campaigns in July 2015 and July 2017.

As a result, our high temporal and spatial resolution data reveals the influence of tides on the opening of the crack. For both observed events, the cracks were likely water-filled and deepened by hydro-fracturing, and the tides may have caused fatigue crack growth. The ice flow model Elmer/Ice is used to analyse the observations further. In particular, we use observed surface ice flow velocities to infer the crevasse depth and water level in the crack prior to the calving events.

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P 13.12
State and evolution of thermal conditions of a small ice cap on Disko Island, West Greenland

Andreas Vieli [1]

[1] *Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zürich (andreas.vieli@geo.uzh.ch)*

Independent marginal ice caps around the Greenland ice sheet often have relatively low-lying accumulation areas that experience summer melt and thus are expected to have relatively warm or even temperate conditions, but observations and our understanding of their thermal state are limited. Furthermore, with the recent rapid warming and related enhanced melt, the conditions at the surface boundary are currently rapidly changing.

In this study, the thermal state and evolution of Lyngmark ice cap on Disko Island is investigated by means of borehole-temperature observations and numerical modelling. A chain of thermistors is logging temperatures at the ice cap divide to a depth of 19m since March 2018. The measurements show ice temperatures of -3 ^{o}C at the zero annual amplitude depth of 9m, which warm to -1.5 ^{o}C at 19m depth. This data clearly indicates cold conditions in the upper third of the ice cap which is confirmed by the well visible internal layering in depth-radar profiles. But this result is also in contrast to the expected firn conditions in accumulation areas at similar elevations in West Greenland. Further, the rate of temperature increase is found to rapidly decrease with depth indicating a cooling from the surface.

In combination with numerical modelling, the observed temperature profile is explained by the disappearance of the accumulation area in the recent decade and hence the removal of the firn. The lack of a substantial firn-layer does no longer allow the retention of latent heat from refreezing of surface melt-water in the summer and further reduces the insulation of the ice body below from the cold winter temperatures at the surface. Thus, in summary, the atmospheric warming has for this ice cap the somewhat counterintuitive effect of cooling the ice cap which may also impact on it’s flow dynamics.

P 13.13
Reconstructing century-long debris-covered glacier history from observation. How are changes in debris cover, surface topography, mass balance, and flow dynamics connected and interacting?

Nico Mölg [1], Tobias Bolch [1], Andrea Walter [1] & Andreas Vieli [1]

[1] *Department of Geography, University of Zurich, Winterthurerstrasse 198, CH-8057 Zürich (nico.moelg@geo.uzh.ch)*

Debris-covered glaciers often exhibited large, flat, down-wasting tongues at the end of the Little Ice Age (LIA). Many of these show high thinning rates today despite thick debris cover. Existing studies have not considered the dynamic interaction between debris cover and glacier evolution over longer time periods, mostly due to lack of longer-term data. The objective of this study was to investigate this interaction by reconstructing changes of debris cover, glacier geometry and dynamics, and down-wasting features of Zmuttgletscher (Valais, Switzerland), based on historic maps, satellite images, terrestrial and aerial photographs and field observations.

We show that since 1859 debris cover extent has increased from 13% to >30% of the total glacier surface and that the debris is sufficiently thick (commonly 15-20 cm) to reduce ablation compared to clean ice. At the same time, glacier mass balance has with -0.31 ±0.04 m w.e./yr from 1880-2017 been similarly negative as ice-free Swiss glaciers. Changes in length and area have been comparatively small, but velocities have strongly decreased since 2001 resulting in a stagnation of the lower areas of the glacier tongue. Years of positive mass balances in the 1970s and 1980s have led to an increase in flow velocities and a short-term decrease in debris-covered area; the effect of increased mass flux was visible at the terminus until 1995 and was followed by a strong reduction in surface elevation along the tongue, specifically in regions with ice cliffs.

We conclude that debris cover has strongly affected the geometric and dynamic – and less the volumetric – changes of Zmuttgletscher since the end of the LIA and that it is increasingly influencing its evolution.

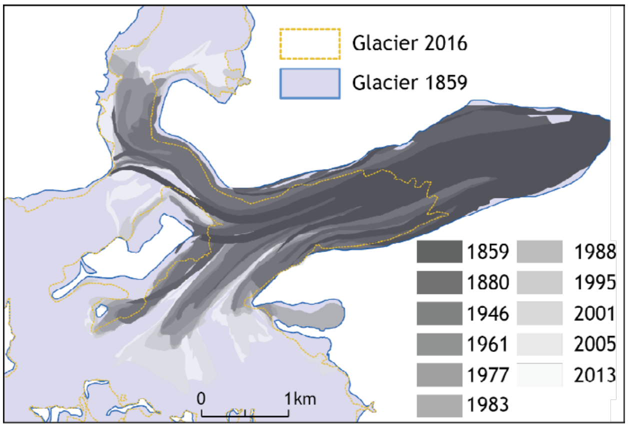

Figure 1. Extent of debris cover and its changes since the end of the LIA. Even though the glacier has retreated in the debris-covered region, debris covers more and more of the total glacier area.

P 13.14
The effect of volcanic eruptions on the long-term evolution of Alpine glaciers

Simon Förster [1], Matthias Huss [1], Martin Funk [1]

[1] *Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, Hönggerbergring 26, CH-8093 Zürich (foerster@vaw.baug.ethz.ch)*

Large volcanic eruptions emit sulfur dioxide which can form aerosol particles in the stratosphere. These aerosol particles interact with and thus reduce incoming solar radiation, cooling the Earth's surface. Since less solar radiation reaches the glaciers' surface, this further reduces melt of ice. Volcanic eruptions may therefore have contributed to glacier advances in the Little Ice Age after several major eruptions around the year 1800. In this study, we quantify how the direct radiation effect on Alpine glaciers compares to the main drivers, air temperature and precipitation.

We developed a simple model for glacier volume change, which includes sensitivities of glacier mass balance to changes in temperature, precipitation, and solar radiation. Different reconstructions of temperature and precipitation are used (e.g. Casty et al. 2005, PAGES2K). In our framework, changes in the solar radiation are solely a function of volcanic aerosols. We use the Easy Volcanic Aerosol model (Toohey et al. 2016) and an extended version of the data set by Stenchikov et al. (1998) to estimate the effect of stratospheric aerosols on incoming radiation.

We present model results for the period 1700 to 2000 and different Alpine glaciers, e.g. Rhonegletscher and Unteraargletscher. The calculated volume changes are compared with available observations from the differencing of digital elevation models.

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P 13.15
Development of a method for the measurement of $\delta^{15}NH_4$ in ice core samples

Prisca Lehmann [1,2], Barbara Seth [1,2], Jochen Schmitt [1,2], Hubertus Fischer [1,2]

*Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstrasse 5, CH-3012 Bern (lehmann@climate.unibe.ch)
[2] *Oeschger Centre for Climate Change Research, University of Bern, Falkenplatz 16, CH-3012 Bern*

Ammonium (NH_4^+) in Antarctic ice samples originates mainly from marine biogenic sources, where it is a key intermediate species in the metabolism of phytoplankton. After the release from the ocean, the formed ammonium-aerosol is transported to the ice sheet, where deposition takes place. In Greenland in addition to this process also ammonium from the nearby landmass, e.g. from biomass burning or soil and plant emissions, can be transported to the ice sheet and deposited on the snow surface.

At our division the Continuous Flow Analysis (CFA) system has a long history and the measurement of high-resolution aerosol chemistry records (e.g. NH_4^+ concentrations) is nowadays a routine application. With the coupling of "CFA" and "mass spectrometry" we want to extend our analytical capabilities and make also the nitrogen isotopic composition of ammonium measurable.

Thereby we envisage two different fields of applications:

1. Quantification of the nutrient cycling efficiency and the biological activity in the Southern Ocean.
2. Differentiation between terrestrial and marine sources of NH_4^+ found in ice cores from Greenland.

The low concentration of ammonium in ice and only small changes in the isotopic ratio make this analysis challenging. The basis of our new $\delta^{15}NH_4$ system is the well-established CFA system, which provides a continuous and contamination-free flow of meltwater containing ammonium. We are currently developing an interface that comprises four main steps: In a first step, the dissolved NH_4^+ is retained by an inorganic absorber (pre-concentration unit). First test, using the cation-exchange and molecular sieve properties of zeolites, are ongoing. The aim is the quantitative retention of ammonium from a larger ice sample in a small volume of zeolite material. After the collection is completed, the zeolite material will be dried under He-flow before ammonia will be desorbed thermally. Secondly, the released NH_3 is quantitatively oxidized to N_2 using Cu/CuO as redox agents (thermal conversion unit). In a third step, combustion side products (i.e. CO, CO_2, NO_x and H_2O) are separated using a series of cryotraps and a gas chromatography system. In the last step, the $\delta^{15}N$ of the purified N_2 is determined by isotopic ratio mass spectrometry (IRMS).

We already constructed and tested the lines for step 2-4 and the oxidative conversion works well for a NH_3-gas-standard. The construction of the pre-concentration unit and the coupling between the water phase (CFA) and gas phase (thermal conversion unit) will be our next step. In our poster we will present the current status of the analytical system.

P 13.16
Towards gas measurements in extremely thinned ice with sublimation extraction and mid-IR spectroscopy

Lars Maechler [1], Bernhard Bereiter [1 2], Phillip Scheidegger [2], Remo Walther [1], Béla Tuzson [2], Jochen Schmitt [1], Lukas Emmenegger [2], Hubertus Fischer [1]

[1] *University of Bern, Climate and Environmental Physics Division, Sidlerstrasse 5, 3012 Bern, Switzerland (maechler@climate.unibe.ch)*
[2] *Swiss Federal Laboratories for Materials Science and Technology, Empa, Überlandstrasse 129, 8600 Dübendorf, Switzerland.*

The European project Beyond EPICA – Oldest Ice Core (BE-OIC) plans to drill an ice core extending over 1.5 Ma, nearly doubling the time span of the existing greenhouse record and covering the time period of the Mid Pleistocene Transition. The oldest section from 1-1.5 Ma is expected to be close to the bedrock and, due to glacial flow, extremely thinned compacting a record of 10,000 yrs into a meter of ice. For a century-scale resolution, the sample vertical extent has to be reduced to cm-scales each containing only 1-2 ml air STP. Within the ERC Advanced Grant deepSlice project we aim to unlock such atmospheric archives by developing a novel coupled semi-continuous sublimation extraction/laser spectroscopy system.

Sublimation is the only dry method that extracts 100% of all gas species (Schmitt et al. 2011) avoiding potential issues with gas fractionation that showed to cause offsets between ice cores/different extraction methods (Bereiter et al. 2015). The development of the gas extraction method aims at vertically sublimating an ice sample with subsequent collecting the air via cryo trapping in a dip tube reducing sample loading and conditioning time and hence allowing a high sample throughput. However, there remain several challenges: the heat transport within the sample could induce subsurface melting or lateral sublimation, and inhomogeneity in the ice or of the radiation field, delivering the heat, could create a spatial inhomogeneous sublimation front.

The custom-made dual-laser spectrometer developed in this context measures simultaneously CO_2, CH_4 and N_2O concentrations and $\delta^{13}C(CO_2)$ isotope ratios in such small air samples without consuming the sample. The analytical approach is based on direct absorption using two Quantum Cascade Lasers emitting at 4.34 and 7.87 µm, respectively. The main challenge here stems from the small sample volume, which requires high precision and stability of the electronical and optical part of the system. For both systems (extraction and analysis) gas adsorption/desorption effects in the sample line add an additional complication.

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P 13.17
Calibration of the new wet-extraction system for CH_4 and N_2O, and plans for high-resolution measurements in the EPICA Dome C ice core (EDC)

Loïc Schmidely, Michael Bock, Christoph Nehrbass-Ahles, Jochen Schmitt, Hubertus Fischer and Thomas Stocker

Climate and Environmental Physics, Physics Institute, University of Bern
Oeschger Centre for Climate Change Research, University of Bern

Reconstructions of past CH_4, N_2O and CO_2 molar ratios from polar ice cores are extremely valuable to understand the coupling between greenhouse gases (GHG) and the climate system at decadal to orbital timescales. In the context of the ongoing climate change, a detailed understanding of past natural GHG variability and feedback mechanisms with global temperature is crucial to constrain the future evolution of the climate system.

To retrieve GHG molar ratios from ice core samples we employ a new extraction technique recently developed in our division coupled to a gas chromatograph. This extraction technique has already been successfully applied for isotope ratio measurements (Schmitt et al., 2014). It is characterized by a continuous vacuum extraction of the trapped gases and subsequent collection on an active coal adsorber. Apart from the high extraction efficiency, the main advantage is the low pressure in the sample vessel ensuring efficient extraction of soluble gases like N_2O.

Our efforts were recently devoted to precisely determine the blank of our instrument. For this purpose we built an injection system enabling the addition of standard gases over melting gas-free ice, reproducing the pressure and temperature conditions prevailing during gas extraction from an ice core sample. The offset in molar ratios between standard gases measured with a reference line and the standards injected over ice represents the blank of the device, integrating all sources modifying GHG abundances.

Our new instrument will be used to increase the temporal resolution of the EPICA Dome C (EDC) GHG record which consistently documented the natural variations of CH_4 and N_2O in the past 800'000 years (Loulergue, 2008, Schilt, 2010). Thanks to this knowledge and our capacity of measuring smaller amount of ice with augmented precision, we aim at zooming into selected abrupt climate fluctuations, for which our understanding of the dynamics of GHG and their interplay with temperature is still suffering from a lack of data. This will allow to better estimate the natural rate of change of GHG and to unveil unresolved fast GHG fluctuations (Bereiter, 2012, Nehrbass-Ahles, in prep.).

Our first measurements will focus on the last interglacial (LIG, 130 – 115 kyrs BP) with the goal of determining the timing of CO_2 changes with respect to CH_4 at the end of the penultimate deglaciation and during an abrupt antarctic warming episode at the end of the LIG. Because of the direct coupling of CH_4 and Northern-hemisphere temperature perturbations the combination of both GHG records will help pinpointing CO_2 sources during these abrupt release episodes.

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P 13.18
Exploring centennial-scale CO_2 reconstruction in the last interglacial

Lucas Silva, Christoph Nehrbass-Ahles, Loïc Schmidely, Jochen Schmitt, Hubertus Fischer, Thomas F. Stocker

Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstrasse 5, CH-3012 Bern (silva@climate.unibe.ch)

Ice cores represent the only direct atmospheric archive to reconstruct past CO_2 atmospheric levels by analysing ancient air trapped in bubbles in the ice. While CO_2 concentrations have been documented over the last 800,000 years (800 kyr), insufficient resolution in many intervals precludes uncovering fine structure on the sub-millenial scale (Lüthi et al 2008). Restricted ice availability and difficulties with traditional CO_2 dry extraction techniques typically inhibit high-resolution data. In this paper we present a new (preliminary) CO_2 dataset for Marine Isotope Stage 5 from EPICA Dome C improving the available resolution by a factor of three. Discrete sampling with our Centrifugal Ice Microtome (CIM; Bereiter et al 2013) achieved ±1 ppm in precision and approximately 250 yr in resolution over the interval 104-135 kyr BP. The reconstruction shows a remarkably stable interglacial period between 127 and 115 kyr at 277 ppm and hints at potentially rapid CO_2 variations during Termination II. Future measurements will increase the resolution of the dataset to 100 yr, delivering a CO_2 record of significant value for our understanding of the last interglacial climate conditions and its relationship with the Holocene (Marcott et al 2014).

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P 13.19
Combining exposure dating, finite-element modelling, and feature tracking to decipher rockglacier evolution: A case study from the Bleis Marscha rockglacier (Val d'Err, Grisons)

Dominik Amschwand [1], Susan Ivy-Ochs [2], Marcel Frehner [1], Olivia Kronig [2], Marcus Christl [2]

[1] Geological Institute, ETH Zürich, Sonneggstrasse 5, 8092 Zürich (adominik@student.ethz.ch)
[2] Laboratory of Ion Beam Physics, ETH Zürich, Otto-Stern-Weg 5, 8093 Zürich

We attempt to reconstruct the formation of the *Bleis Marscha* rockglacier in the Val d'Err, Grisons (Switzerland). It is a one kilometer long, multi-unit talus rockglacier (Barsch 1996) with an active upper part that overrides a lower part. Lichen-covered boulders, vegetated, stabilized slopes, and signs of settling suggest that the parts below ~2500 m a.s.l. are relict. Internal front scarps separate the rockglacier into different units, each with its own activity phase. Morphological evidence suggests that the rockglacier started forming in the earliest Holocene.

Surface exposure dating with cosmogenic ^{10}Be and ^{36}Cl places a temporal framework (ka scale) on rockglacier movement periods (Ivy-Ochs et al. 2009). Furthermore, the present-day dynamics are numerically modelled using a two-dimensional finite-element approach to gain insights into the mechanical and material properties. Deformation above the shear zone is well captured by a linear viscous flow law (Frehner et al. 2015). The model is constrained with horizontal surface velocities obtained from feature-tracking analysis of multitemporal orthorectified aerial images (Messerli & Grinsted 2015).

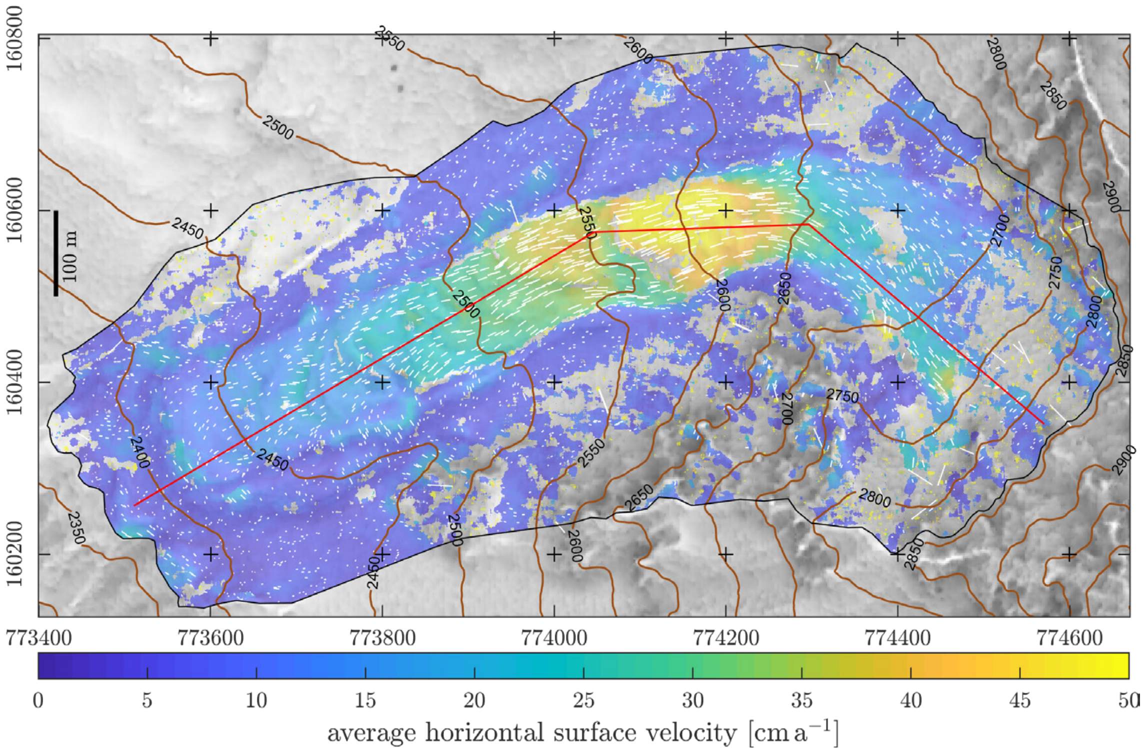

Figure 1. Noise-filtered horizontal surface velocity field 2003-2012 as obtained from feature-tracking analysis of orthorectified aerial images, draped over a sky-view map. Magnitude shown by colours, direction by white arrows. Significance level is 5 cm/a.

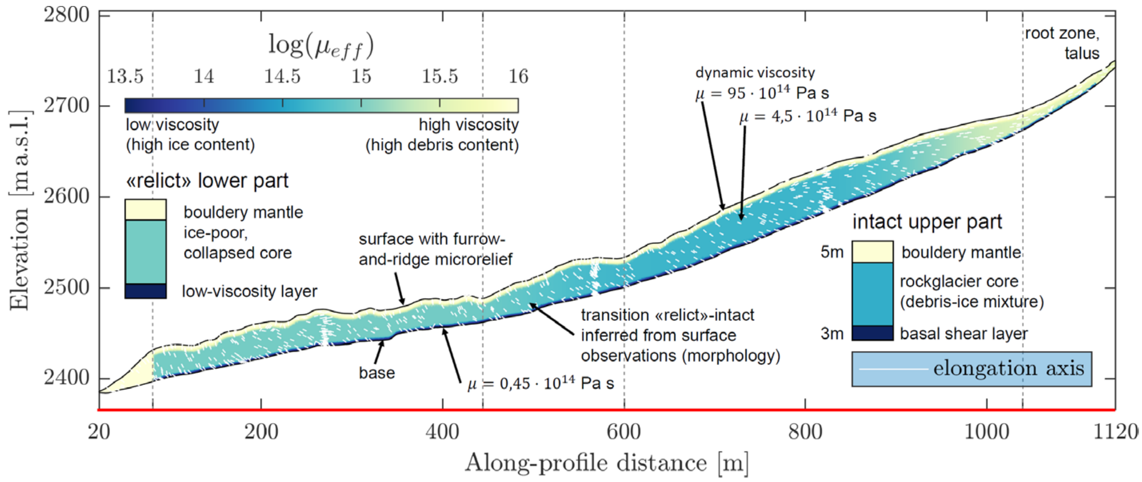

Figure 2. Inferred viscosity structure along a longitudinal section (trace in Fig. 1). Viscosity is interpreted as a proxy for ice and liquid water content.

An illumination-invariant method for correlating the orthophotos (Fitch 2002) yielded reliable displacements on the rugged rockglacier surface. The image correlation results (Fig. 1) support the subdivision of the *Bleis Marscha* rockglacer in an active upper part, characterised by moderate to high surface velocities controlled by the topography on a 100-m scale, and a relict, collapsing lower part, characterised by an irregular surface velocity field strongly coupled to the small-scale topography ("effet camembert"). However, surface velocities of up to 30 cm/a on the apparently relict part could only be numerically reproduced assuming a considerable fraction of ice and/or water that weakens the material (Fig. 2). The subsurface ice either has been preserved throughout the Holocene or has reformed more recently.

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P 13.20
Effects of ice cover and permafrost on groundwater flow during the last glacial cycle in the Swiss lowlands

Denis Cohen [1], Thomas Zwinger [2], Mark Person [1], Wilfried Haeberli [3], & Urs H. Fischer [4]

[1] Department of Earth and Environmental Science, New Mexico Tech, Socorro, NM, USA (denis.cohen@gmail.com)
[2] CSC – IT Center for Science Ltd, Espoo, Finland
[3] Department of Geography, University of Zurich, Zurich, Switzerland
[4] Nagra, Wettingen, Switzerland

There are compelling evidences that Pleistocene glaciations affected groundwater flow systems. Loading by ice sheets and glaciers and development of permafrost can affect the hydraulic and thermal properties of rocks and sediments beneath and along the margins of the ice, and thus can modify local groundwater flow patterns and discharge areas (e.g. Bense & Person 2008). Conditions at the bed of the ice mass, whether frozen or at the melting temperature, can also impact groundwater recharge into aquifers. Knowing and understanding modifications to groundwater flow systems during glaciation is important for the long-term safety of deep geological repositories for high-level radioactive wastes. Here, we couple a new groundwater flow and permafrost model (Hartikainen et al 2018) to a glacier evolution model implemented in Elmer/Ice (Gagliardini et al 2013). The system is applied to a two-dimensional cross-section of the Swiss Alps and lowlands that includes the main geological formations down to a depth of 15 km (Figure 1). Preliminary simulations of groundwater flow use a fixed LGM climate and glacier geometry. Groundwater flow simulations explore the effects of ice loading (Figure 2) and the connection between the autochtonous aquifer beneath the Alps and the Malm aquifer in the lowlands on the patterns and flux of groundwater in the lower Thur valley. Other simulations explore the effect of permafrost thickness on groundwater flow paths and discharge area near the repository siting region. Model results show that ice loading, aquifer connection, and values of substrate permeabilities have a significant effect on the groundwater flow patterns and fluxes in the Swiss lowlands.

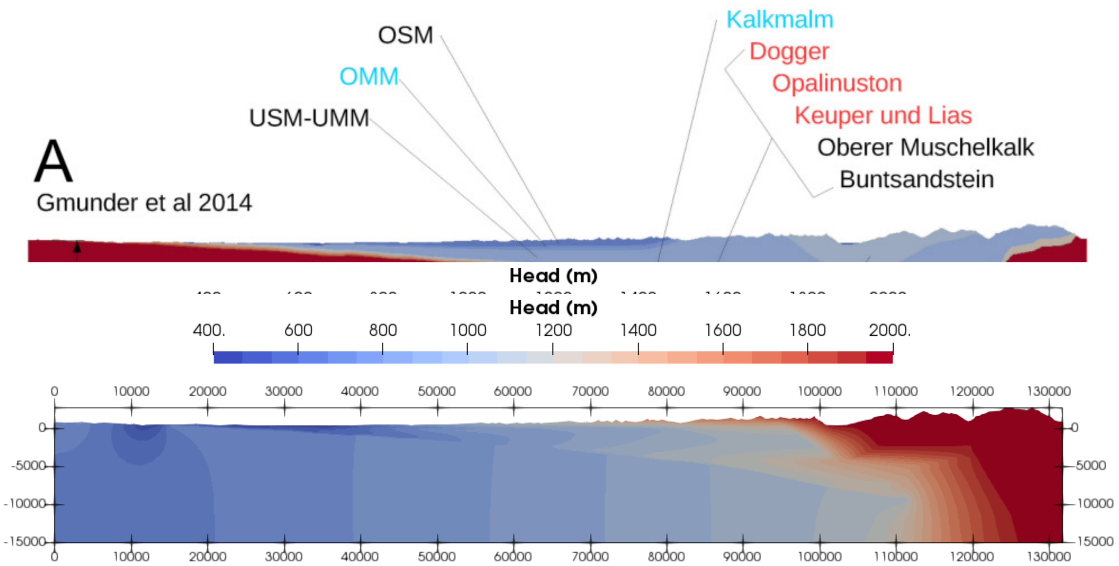

Figure 2. Calculated heads during interglacial (top) and at glacial maximum (bottom). Significant higher heads in the Alps are caused by ice loading.

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P 13.21
Modeling permafrost occurrence, glacier-bed topography and possible future lakes for assessing changing hazard conditions in cold mountain regions

Wilfried Haeberli [1], Florence Magnin [2 3] & Andreas Linsbauer [1 4]

[1] *Geography Department, University of Zurich, Winterthurerstrasse 190, CH-8057 Zürich (wilfried.haeberli@geo.uzh.ch)*
[2] *Department of Geosciences, University of Oslo, Postbox 1047, Blindern, 0316 Oslo, Norway (florence.magnin@geo.uio.no)*
[3] *EDYTEM Lab, Université Savoie Mont Blanc, CNRS, 5 bd de la mer Caspienne, F-73376 Le Bourget du Lac, France*
[4] *Department of Geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg*

Under conditions of continued global warming in cold mountains, most glaciers tend to disappear within decades while the degradation of permafrost on exposed slopes can take centuries. Glacial landscapes are therefore rapidly but for extended future time periods transforming into periglacial landscapes with permafrost still existing but in strong thermal disequilibrium. Modeling such new landscapes is an important emerging research field. One key aspect thereby concerns changing hazard conditions related to decreasing slope stability due to permafrost degradation and glacial debuttressing, possibly causing impact/flood waves from rock/ice avalanchs into new lakes (Haeberli et al. 2017). Anticipation of critical future situations requires combined modeling of permafrost occurrence patterns (Magnin et al. 2017) and glacier-bed topographies (Linsbauer et al. 2016).

Figure 1 shows an example from an ongoing study in the Mont Blanc region, French Alps. It can be seen that possible future lakes will not only form at the immediate foot of large and steep permafrost slopes, for instance at Aiguille Verte and Les Droites, but also close to oversteepened, glacially de-buttressed lateral slopes that will be subject to seasonal frost and permafrost formation. Such new lakes exposed to potential rock/ice avalanches are multipliers of hazards and risks in the region. The probability of catastrophic events cannot be quantified but undoubtedly increases with continued ice vanishing. As a next step, rapid-simple flood/debris-flow modeling should help with defining priorities concerning damage potentials and risks and with early planning of corresponding measures to enable sustainable practical solutions.

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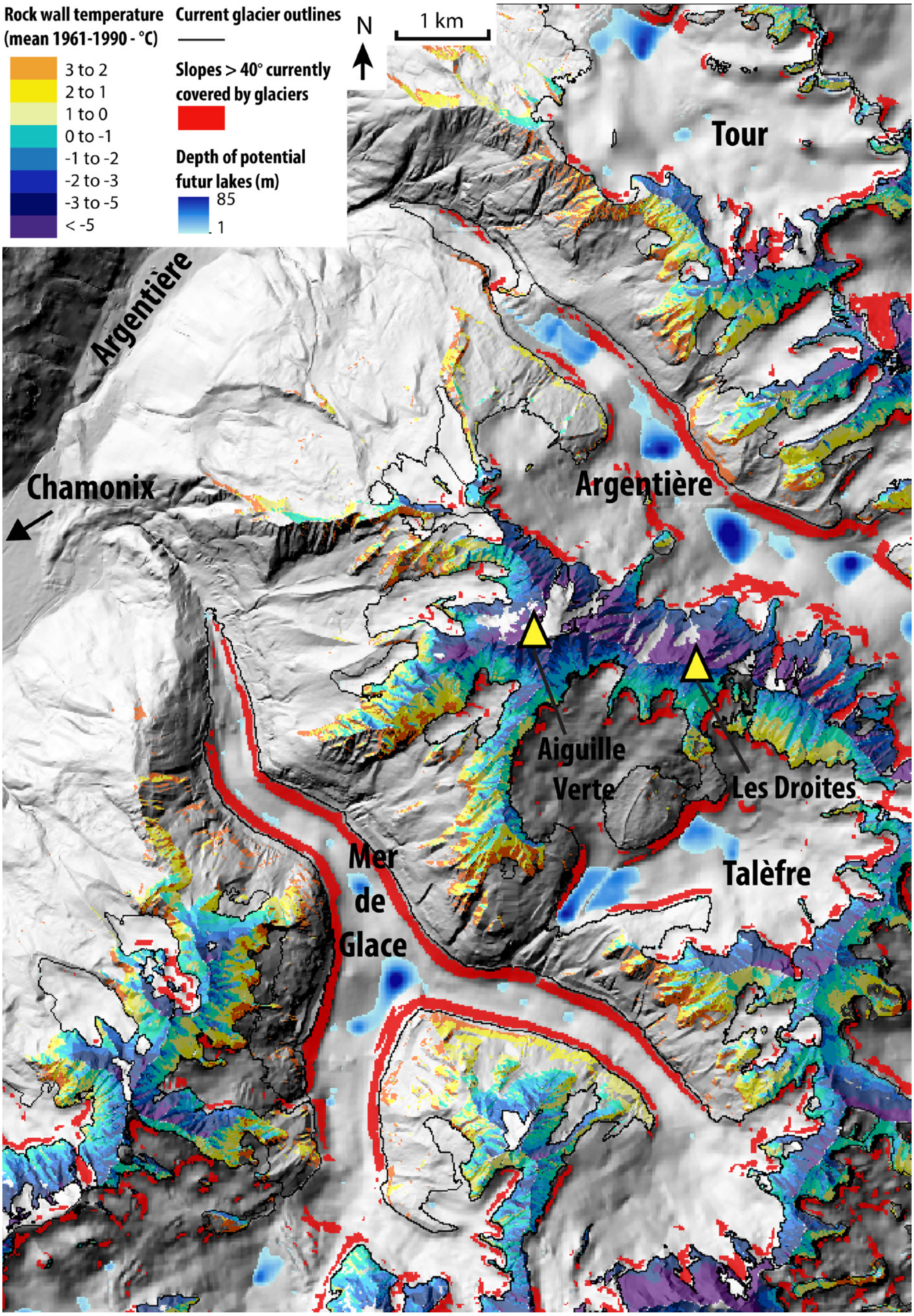

Figure 1. Mer de Glace, Glacier d'Argentière and surroundings with modeled present rock-wall temperatures, oversteepened and overdeepened parts of glacier beds. This information can be used for early anticipation of potential future risks related to a high-mountain environment in conditions beyond historical precedence and experience.

P 13.22
Towards a joint database and statistical analysis of electrical resistivity and refraction seismic tomography datasets in mountain permafrost

Coline Mollaret, Cécile Pellet, Christin Hilbich & Christian Hauck

Departement of geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg (coline.mollaret@unifr.ch)

Electrical Resistivity Tomography (ERT) and Refraction Seismic Tomography (RST) are commonly applied methods for the detection, mapping, characterisation and monitoring of permafrost occurrences around the world (Kneisel et al. 2008, Hauck 2013). The resulting datasets are either processed and interpreted individually or in a joint manner, including quantitative estimates of subsurface ice and water contents (e.g. Pellet et al. 2016) and joint inversion approaches (cf. Mollaret et al. 2018, this conference). However, ERT and RST datasets are up to now neither stored in joint databases, nor analysed in a comparative way with datasets from other permafrost occurrences worldwide.

In this contribution, we want to present a first step towards a joint database of ERT and RST datasets from coincident permafrost profiles over a wide range of countries, mountain ranges, locations, morphologies and subsurface ice contents. More than 100 profiles from the European Alps, the central European middle mountains, Scandinavia, the Andes and Antarctica were analysed regarding electrical resistivities and P-wave velocity distributions as well as common statistical parameters. As electrical and seismic data can be used as proxies for subsurface and ice and water contents in permafrost areas we believe that a joint database will make a useful contribution to the existing borehole temperature database of GTN-P (Biskaborn et al. 2015).

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P 13.23
Establishing a permafrost monitoring network in the Bernese Alps: geophysical characterisation of potential monitoring sites and validation of permafrost distribution models

Christin Hilbich [1], Christian Hauck [1], Nils Hählen [2]

[1] *Department of Geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg (christin.hilbich@unifr.ch)*
[2] *Department of Natural Hazards, Canton of Bern, Schloss 2, CH-3800 Interlaken*

Permafrost monitoring has a long tradition in Switzerland and is operational since 2000 within the PERMOS network (www.permos.ch). Distribution of monitoring sites is however not homogeneous with an increased concentration of sites towards the Valais Alps in the West and the Grisons in the East, while the Bernese and Central Alps are underrepresented. The canton of Berne therefore recently initiated the establishment of a long-term permafrost monitoring network within the Bernese Alps, with the main goal to detect and map permafrost occurrences, monitor their long-term evolution and evaluate the probability of natural hazards related to degrading permafrost.

As a first step, potential monitoring sites are selected based on the modelled permafrost distribution (Alpine permafrost index map by Boeckli et al. 2012, and Map of potential permafrost distribution by BAFU 2005), and promising sites are investigated by means of geophysical measurements (Electrical Resistivity Tomography/Refraction Seismic Tomography), ground surface temperature measurements as well as geomorphological interpretation. From the joint analysis of all data, propositions for new boreholes are made.

In this contribution we will present a data set of more than 30 geophysical profiles from more than 14 new locations (without previous information). As many of the sites of interest are located close to the lower boundary of potential permafrost distribution (~2500 m asl), this extensive geophysical data set can further be used for the validation of existing permafrost distribution models for this region. We here present a comparative analysis of geophysical-based characterisation of the permafrost distribution and the modelled permafrost probability for the respective locations. The results confirm that geophysical surveying presents a cost-effective approach to detect permafrost over larger areas and evaluate permafrost distribution models with an independent data set.

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P 13.24
Interactive snow profile edition with niViz

Mathias Bavay [1], Thomas Egger [2], Charles Fierz [1]

[1] *WSL Institut für Schnee und Lawinenforschung SLF, Flüelastrasse 11, CH-7260 Davos Dorf (bavay@slf.ch)*
[2] *Egger Consulting, Postgasse 2, A-1010 Vienna, Austria*

The niViz software has been designed to visualize snow profiles and timeseries of profiles either online or offline, within a web browser. This applies to both measured and simulated data, based around the CAAML snow profile standard. A new module has been developed to create or edit snow profiles interactively. This module allows editing all properties present into the CAAML standard: metadata (including weather conditions, surface conditions or observer/station/profile ID); stratigraphy with all possible grain shapes subclasses, wetness or hardness and optional comments for each layer; multiple profiles of temperature, density, liquid water content, SSA, ram resistance or snow micropenetrometer profiles (that can be imported as CSV); stability information (as various stability tests, from classical compression test to propagation saw tests). Thanks to the standardized nature of CAAML, the generated profiles can then be exchanged between the many worldwide institutions supporting the standard.

This Javascript library and application is available under an Open Source license (GNU affero General Public License) thanks to the funding provided by an international consortium of more than ten institutions.

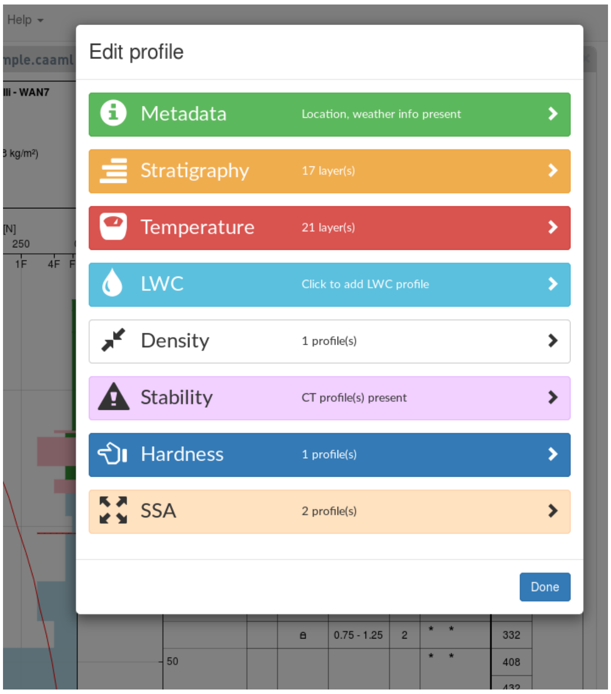

Figure 1. Modal dialogue to edit an existing profile (in the background).

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P 13.25
Prediction of snow failure: mission impossible?

Achille Capelli [1], Ingrid Reiweger [2], Jürg Schweizer [1]

[1] *WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, 7260 Davos Dorf, Switzerland, (achille.capelli@slf.ch)*
[2] *Institute of Mountain Risk Engineering, Department of Civil Engineering and Natural Hazards, BOKU University of Natural Resources and Life Sciences, Peter-Jordan-Strasse 82, 1190 Wien, Austria*

Slab avalanches are caused by a crack forming and propagating in a weak layer within the snow cover, which eventually causes the detachment of the overlying cohesive slab. It would be, therefore, useful to be able to predict the nucleation of the initial failure. Failure in heterogeneous materials, such as snow, is normally preceded by a progressive damage process. Therefore, monitoring this progressive damage should allow predicting the failure point. A possibility to monitor this damage process is to analyze the acoustic emissions (AE) generated by the damage (micro-cracking). We performed snow failure experiments in a cold laboratory and evaluated possible precursory features in the generated AE preceding failure. In addition, to the known differences in the deformational behavior as a function of the loading rate, also the AE characteristics clearly depended on the loading rate. Whereas, for experiments at high loading rates we identified some features that may be used to predict failure, for low loading rates these AE features were not or just partially present. In other words, at low loading rates failure seemed to occur abruptly, i.e. without obvious changes in the damage process. We then used a fiber bundle model to investigate the reasons of the observed differences in the AE signature. The ability of forming new bonds due to rapid sintering and viscous deformation causing load redistribution in the ice matrix, two particular properties of ice, were implemented in the FBM. Our FBM simulations revealed that both time dependent processes were necessary to reproduce the observed loading rate dependent differences in the mechanical deformation and AE signature of snow, and that at slow loading rates the failure can occur abruptly without precursors. Hence simulations as well as experimental results suggest that due to the rapid sintering and viscous deformation of the ice matrix the failure of snow cannot be predicted for low loading rates, at least not with the methods we employed. Hence applying AE techniques for snow avalanche prediction in the field seems not feasible. Still, the found AE characteristics may be useful to assess the mechanisms beyond the failure nucleation process that lead to the release of natural slab avalanches.

P 13.26
How meteorological input uncertainty affect modeled snow instability

Bettina Richter[1], Alec van Herwijnen[1], Mathias W. Rotach[2], Jürg Schweizer[1]

[1] WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos (bettina.richter@slf.ch)
[2] Department of Atmospheric and Cryospheric Sciences, ACINN, Innrain 52f, A-6020 Innsbruck

Snow avalanches can endanger roads, villages and human lives. When assessing the avalanche danger in the context of avalanche forecasting, data on current snowpack and meteorological conditions are evaluated in combination with weather forecasts. Snowpack observations include data on snow stratigraphy and snow instability. The temporal and spatial resolution of snowpack data is, however, very limited. Detailed snow cover models, which simulate the full snowpack stratigraphy, can help fill this gap, in particular if they also provide snow instability information. Snow cover models are forced with meteorological data from either automatic weather stations or numerical weather models, and snow instability criteria can be derived from simulated stratigraphy. To perform spatial snow cover simulations for numerical avalanche forecasting, interpolation and downscaling of meteorological data is required, which can introduce uncertainties. The repercussions of these uncertainties on modeled snow instability remain mostly unknown.

We therefore investigated how meteorological input uncertainty influenced modeled snow instability using a global sensitivity analysis. We used the model SNOWPACK to simulate snow instability, i.e. the skier stability index and the critical crack length, for a field site equipped with an automatic weather station providing the necessary input for the model. We performed simulations for the winter season 2016-2017, when one weak layer persisted for the entire season and affected the avalanche activity within the region of Davos, Switzerland. Uncertainty ranges for precipitation, air temperature, relative humidity, wind, and short- and long-wave radiation covered typical differences observed within a distance of 2 km and an elevation change of 200 m. We selected the weak basal layer that formed between 16 November 2016 and 2 January 2017. Only simulated snow layers that were deposited between these two dates and consisted of either depth hoar, surface hoar, facets and rounded facets were considered as weak layer. We independently investigated the influence of meteorological input uncertainty in two scenarios covering distinct periods of a) weak layer formation and b) slab formation. For each scenario, 14,000 simulations were performed.

Results showed that during the weak layer formation period, the evolution of weak layer properties and subsequent snow instability were sensitive to all input parameters. In particular, increasing air temperature and increasing precipitation led to higher stability indices. Once a certain weak layer had formed, precipitation was the most prominent driver for snow instability during the slab formation period. While with increasing precipitation the skier stability index decreased, the critical crack length increased. While data from different winters are required to confirm these findings, such results will help with selecting model resolution and interpreting spatial snow simulations for numerical avalanche forecasting.