12. Cryospheric Sciences

Matthias Huss, Theo Jenk, Kathrin Naegeli, Nadine Salzmann, Andreas Vieli

Swiss Snow, Ice and Permafrost Society

TALKS:

12.1 Bannwart J., Zemp M., Rastner P., Paul F., McNabb R.: Towards a global assessment of glacier change – A focus on satellite based geodetic mass changes in polar regions

12.2 Clerx N., Machguth H., Tedstone A.: Hydrological processes at the runoff limit on the Greenland Ice Sheet


12.4 Guidicelli M., Gugertl R., Gabella M., Salzmann N.: Improving temporal and spatial estimates of solid precipitation and snow accumulation in high mountain regions with statistically-based models

12.5 Haugeneder M., Jonas T., Reynolds D., Lehning M., Mott R.: Experiments on wind-driven heat exchange processes over melting snow

12.6 Hellmann S., Grab M., Bauder A., Maurer H.: Detecting the crystal orientation fabrics of an ice core with non-invasive ultrasonic measurements

12.7 Kneib M., Miles E., Buri P., Shaw T., McCarthy M., Fugger S., Pellicciotti F.: Improving the representation of ice cliffs and supraglacial ponds in distributed glacier melt models

12.8 Koutantou K., Mazzotti G., Jonas T., Brunner P.: Accessing forest snow cover dynamics in steep mountain terrain using UAV-based Lidar data

12.9 Miles E., McCarthy M., Dehecq A., Kneib M., Fugger S., Pellicciotti F.: Specific mass balance and health of glaciers in High Mountain Asia derived from the continuity equation

12.10 Mollaret C., Hilbich C., Pellet C., Hauck C.: Towards a geoelectrical database for permafrost monitoring to enable the processing and repetition of historical measurements

12.11 Noetzli J., Pellet C., & the PERMOS Scientific Committee: Permafrost warming in the Swiss Alps – 20 years of measurement in the framework of PERMOS

12.12 Pohle A., Werder M.A., Farinotti D.: Characterising englacial R-channels using artificial moulins


12.14 Tielidze L.: The history of glacier study of the Greater Caucasus and current state of observation
POSTERS:

P 12.1 Amschwand D., Scherler M., Hoelzle M., Krummenacher B., Kienholz C., Gubler H.: A ‘subsurface weather station’ to measure boulder-mantle heat fluxes on Murtèl rock glacier

P 12.2 Cicoira A., Ferguson J., Dussaillant I., Mölg N., Vieli A.: Unveiling the secrets of the debris cover of the Zmutt Glacier (Valais – CH)

P 12.3 Compagno L., Huss M., McCarthy M.J., Miles E.S., Pellicciotti F., Zekollari H., Farinotti D.: Impact of debris cover on future evolution of HMA glaciers

P 12.4 Ferguson J., Cicoira A., Dussaillant I., Mölg N., Vieli A.: Nonlinear feedbacks driving pattern formation on debris-covered glaciers

P 12.5 Kurzböck C., Geibel L., Huss M., Bauder A.: Rescue, Documentation and Re-analysis of Swiss Glacier Monitoring Data


P 12.7 Lüthi M., Thalmann M., Rusca S., Cicoira A., Mölg N.: Multispectral and thermal mapping of the polythermal Gorner-/Grenzgletscher terminus

P 12.8 Macfarlane A., Wagner D., Dadic R., Hämmerle S., Schneebeeli M.: The snow microstructure on sea ice – first results from the MOSAIc expedition

P 12.9 Mölg N., Huggel C., Herold T., Storck F., Odermatt D.: Swiss-wide post-Little Ice Age glacial lake evolution

P 12.10 Pruessner L., Huss M., Farinotti D.: A framework for modelling rock glaciers and permafrost at the basin-scale in high Alpine catchments

P 12.11 Schauwecker S., Palma G., MacDonell S., Goubanova K.: Challenges of estimating the snow-rain transition zone in the semi-arid Andes


P 12.13 Tompkin C., Leinss S.: The Role of Local Resolution Weighting in Automatic Avalanche Mapping with Sentinel-1


P 12.15 Landmann J.M., Küssch H.R., Huss M., Ogier C., Farinotti D.: CRAMPON – a workflow for obtaining and assimilating near real-time glacier mass balance observations

P 12.16 Fugger S., McCarthy M., Fyffe C., Miles E., Fatichi S., Kneib M., Yang W., Wagnon P., Pellicciotti F.: Understanding monsoon controls on the energy- and mass-balance of glaciers in High Mountain Asia

P 12.17 Wicky J., Hauck C.: The thermal behaviour of a low elevation cold talus slope: Insights through numerical modeling
12.1
Towards a global assessment of glacier change – A focus on satellite based geodetic mass changes in polar regions


*Department of Geography, University of Zurich, Zurich, Switzerland (jacqueline.bannwart@geo.uzh.ch)
**School of Geography and Environmental Sciences, Ulster University, Coleraine, United Kingdom

Glaciers all over the world are shrinking and are expected to continue doing so, with or without further temperature increase, as current glacier extents are out of balance with the current climatic conditions. For larger scale purposes, the geodetic method comes in place, which enables to assess the global sea-level rise contribution of glaciers. The Fluctuations of Glaciers (FoG) database at the WGMS collects datasets derived from remote sensing platforms (i.e. geodetic glacier elevation change data). The Copernicus Climate Change Service (C3S) aims and is in progress to extend the FoG database in space, time and to improve its regional representativeness. This work, as part of the C3S project, contributes to this aim by (A) improving estimates of glacier loss and sea-level rise by enhancing data coverage temporally and spatially, and (B) tackling the challenges associated with the application of DEMs for geodetic mass balance assessments (i.e. data voids, radar penetration).

We will present the basic concept of the C3S, what has been achieved since its launch in 2017, challenges we are facing as well as what we plan to tackle in the future. By doing so, the previously published study about glacier elevation changes of Greenlandic glaciers from 1980 to 2012 will be discussed. This study presents for the first time glacier-wide elevation changes for a large sample of Greenland peripheral glaciers and improved the assessments of the contribution of glaciers to sea-level rise.
12.2
Hydrological processes at the runoff limit on the Greenland Ice Sheet

Nicole Clerx*, Horst Machguth*, Andrew Tedstone*

*Department of Geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg (nicole.clerx@unifr.ch)

Surface meltwater runoff is responsible for roughly 60% of the current mass loss of the Greenland ice sheet. The runoff limit is the highest elevation from which meltwater finds its way off the ice sheet; above the runoff meltwater is captured by refreezing in the snow and firn. The location of the runoff limit therefore plays an important role in the mass balance of the Greenland ice sheet. Recent findings have shown that widespread ice slabs have developed on the Greenland ice sheet close to the runoff limit (Machguth et al., 2016). These ice slabs might impede meltwater from percolation and refreezing and accelerate surface runoff.

Hydrological processes in snow have been studied extensively, but little is known about meltwater flow through snow and firn on the Greenland ice sheet, and no direct evidence exists on how runoff is affected by the ice slabs.

In July 2020 we carried out a field campaign at 1760 m a.s.l. around the runoff limit on the Greenland ice sheet, near the KAN_U weather station in south-west Greenland. We did in situ measurements to study hydrological processes in relation to the location of the runoff limit and its evolution in time and space. We carried out snow pit and borehole measurements to assess firn stratigraphy, crystal structure, porosity and height of the meltwater table. Salt dilution and dye tracing experiments were performed to measure meltwater flow velocity and direction. Here we present first results from these measurements.

Substantial amounts of liquid water were encountered. The water flows towards intermittent supraglacial drainage systems through snow and firn overlying the ice slab. Measured flow velocities inside the snow matrix range from 3-15 m/hr. Meltwater flow behaviour and -direction is primarily controlled by regional surface slope but modified by local stratigraphic features such as ice lenses, ice slab surface undulations and the presence of supraglacial river beds from previous melt seasons.

These results show that significant quantities of meltwater flow at relatively high velocities atop the ice slab towards supraglacial discharge networks, allowing the water to leave the ice sheet through these systems. We conclude that the presence of ice slabs increases meltwater runoff. The relevance of this process to ice sheet mass balance remains to be quantified in future research.

REFERENCES
Machguth, H.; MacFerrin, M.; van As, D.; Box, J.E.; Charalampidis, C.; Colgan, W.; Fausto, R.S.; Meijer, H.A.J.; Mosley-Thompson, E.; van de Wal, R.S.W., 2016: Greenland meltwater storage in firm limited by near-surface ice formation, Nature Climate Change, 6, 390-393.
12.3
Future glacial lakes of the world – characteristics, risks and opportunities


* Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich (louis.frey@geo.uzh.ch)
** Laboratory of Hydraulics, Hydrogeology and Glaciology (VAW), ETH Zurich, Hönggerbergring 26, CH-8093 Zurich
*** Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, CH-8903 Birmensdorf

Accelerated retreat of glaciers is observed all around the world and is seen as an icon of climate change. This retreat is often accompanied by the formation of new glacial lakes, with remarkable and far-reaching impacts on the downstream population. These impacts include exposure to potential hazards such as glacier lake outburst floods (GLOFs), but such new lakes also provide potential opportunities, such as for hydropower exploitation or irrigation. To anticipate the formation of such glacial lakes and related phenomena for the future at global scale, we produce an inventory of all potential future glacial lakes of the world.

To do so, we draw on data produced by Farinotti et al. (2019), who provided digital elevation models (DEMs) of the glacier surfaces and an ensemble of associated ice thickness distributions for all glaciers on earth, based on up to four different models and a composite.

Using standard GIS procedures (ice thickness subtraction from the surface DEM, sink-filling, and raster to polygon conversion), and assuming complete melting of all glaciers and ignoring possible filling of sinks with sediment, we were able to derive an inventory of all future glacial lakes of the world. A special challenge was related to handling the large amount of data that was required for the analysis. With around 215,000 glaciers and up to five realisations of the ice thickness for each glacier, a highly automated processing approach using parallelization in a high-performance computing environment was applied. Processing of the ensemble of ice thickness realisations allows for a first-order quantification of uncertainties. Additionally, a validation of the ensemble of derived bedrock distributions against GPR measurements from Swiss glaciers with regard to reproduction of future glacier lakes was performed. We further plan to compute the topographic potential of each future lake for ice/rock avalanches (as potential GLOF triggers) (Romstad et al. 2009; Allen et al. 2019), and simulate GLOF trajectories and formation period for each lake (results pending).

Our results indicate that the total number of future glacial lakes in the world can reach 400,000, with a total lake volume of about 4000 km³, a total lake surface area of around 70,000 km² (i.e. close to twice the area of Switzerland). The single largest future glacial lake, located at the Barnes Ice Cap in Baffin Island, Canada, will likely have a volume of about 150 km³. At Konkordiaplatz on Grosser Aletschgletscher, models predict a potential future lake with a volume between 33 and 220 Mio m³. The validation procedure indicated qualitative agreement between models and high accuracies (around 0.9) in reproducing future glacial lakes (binary: lake / no lake), yet no clearly best model emerged and quantitative performance indicators are relatively poor. This result, together with the uncertainties represented by the spread of the ensemble, demands caution in interpreting our results.

Nevertheless, our results allow for a global assessment of hazards, risks and opportunities related to future glacial lakes at regional scales.

REFERENCES
12.4
Improving temporal and spatial estimates of solid precipitation and snow accumulation in high mountain regions with statistically-based models

Matteo Guidicelli*, Rebecca Gugerli*, Marco Gabella** & Nadine Salzmann*

*Département of Geosciences, University of Fribourg, Chemin du Musée 4, CH-1700 Fribourg (matteo.guidicelli@unifr.ch)
**Radar, Satellite, Nowcasting Department, MeteoSwiss, Locarno-Monti, Switzerland

The scarcity and the considerable uncertainties of precipitation observation and estimation in high mountain regions are a major drawback for enhancing our understanding of climatic-cryospheric processes and limits the reduction of uncertainties in related climate impact studies.

We are tackling the scientific challenge of improving precipitation estimates in high mountain regions by combining methods and data from atmospheric and cryospheric sciences. Here, we present a study in the Swiss Alps, which aims to produce temporally and spatially highly resolved estimates of Snow Water Equivalent (SWE) by applying statistical methods. Firstly, a Multiple Linear Regression (MLR) combining weather radar composites (Rad4Alp network of MeteoSwiss) and specifically, the CombiPrecip product with COSMO-1 precipitation estimates and COSMO-1 10 m wind speed estimates is applied to produce temporally highly resolved estimate of solid precipitation. The MLR is trained with SWE from a Cosmic Ray Sensor (CRS) deployed on the glacier de la Plaine Morte. SWE estimates of another CRS located on the Findelgletscher are used to test the MLR estimates.

Secondly, the MLR is applied to the whole glacier area of eight Swiss glaciers. In order to evaluate our results on these glaciers, we compare them with the scattered end of season SWE measurements provided by GLAMOS (Glacier Monitoring Switzerland). The cumulated sums of our MLR estimates show a good agreement with end of season measurements. The difference between ground measurements and the cumulated winter precipitation is partially explainable by the radar visibility, melting and snow drift processes, which depend on the topography and local meteorological conditions.

Thus, we derived several high-resolution topographical indicators from a 25m resolution digital elevation model (DHM25, swisstopo) in order to explain the differences between GLAMOS measurements and our MLR precipitation estimates. The obtained model shows an increase of the correlation and a reduction of the mean bias error with respect to GLAMOS measurements. An example of the cumulated precipitation of the different products and models over the Findelgletscher is reported in figure 1. The final model is further validated with bi-weekly manual SWE measurements of SLF, in order to evaluate the model generalization for high mountain sites without glaciers.

![Maps of cumulated precipitation and GLAMOS observations over the Findelgletscher at the end of the winter season 18/19. (A): Scaled CombiPrecip, (B): Scaled COSMO-1, (C): Phase 1 MLR, based only on Plaine Morte site, (D): Phase 2 MLR, involving topographical parameters.](image-url)

Figure 1. Maps of cumulated precipitation and GLAMOS observations over the Findelgletscher at the end of the winter season 18/19. (A): Scaled CombiPrecip, (B): Scaled COSMO-1, (C): Phase 1 MLR, based only on Plaine Morte site, (D): Phase 2 MLR, involving topographical parameters.
REFERENCES
12.5
Experiments on wind-driven heat exchange processes over melting snow

Michael Haugeneder*, Tobias Jonas*, Dylan Reynolds*, Michael Lehning*,**, Rebecca Mott*

*WSL-Institut für Schnee- und Lawinenforschung SLF, Flüelastraße 11, CH-7260 Davos Dorf (michael.haugeneder@slf.ch)
**CRYOS, School of Architecture, Civil and Environmental Engineering, EPFL, Station 2, CH-1015 Lausanne

Snowmelt runoff predictions in alpine catchments are challenging because of the high spatial variability of the snow cover driven by various snow accumulation and ablation processes. In spring, the coexistence of bare and snow-covered ground engages a number of processes such as the enhanced lateral advection of heat over partial snow cover, the development of internal boundary layers, and atmospheric decoupling effects due to increasing stability at the snow cover. The interdependency of atmospheric conditions, topographic settings and snow coverage remains a challenge to accurately account for these processes in snow melt models.

In this experimental study, we used an Infrared Camera (VarioCam) pointing at thin synthetic projection screens with negligible heat capacity. Using the surface temperature of the screen as a proxy for the air temperature, we obtained a two-dimensional instantaneous measurement. Screens were installed across the transition between snow-free and snow-covered areas for various topographic settings. With measurements taken at 10Hz, we were able to capture the dynamics of turbulent temperature fluctuations over the patchy snow cover at high spatial and temporal resolution. Combined with an ultrasonic anemometer and an eddy covariance sensor, heat advection and turbulent heat fluxes along the projection screens are investigated.

Preliminary results show the formation of a stable internal boundary layer (SIBL), which was temporally highly variable. Our data suggest that the SIBL height is strongly sensitive to the mean near-surface wind speed. Only strong gusts were capable of penetrating through this SIBL leading to an enhanced energy input to the snow surface. With these type of results from our experiments we aim to better understand small scale energy transfer processes over patch snow cover, enabling to improve parameterizations of these processes in coarser-resolution snow melt models.
12.6 Detecting the crystal orientation fabrics of an ice core with non-invasive ultrasonic measurements

Sebastian Hellmann*,**, Melchior Grab*,**, Andreas Bauder*, Hansruedi Maurer*

*Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Hönggerbergring 26, CH-8093 Zurich
(sebastian.hellmann@erdw.ethz.ch)
**Institute of Geophysics, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich

The orientation of the hexagonal ice crystals provides valuable information about the history of the ice of glaciers and ice sheets. The stresses and strain rates force a development of typical crystal orientation fabric (COF) patterns. Typical COF patterns are a single maximum, a girdle structure or multi-maxima patterns. For single maxima, the ice grains and their c-axes are aligned in a certain direction and thus the basal planes are suitably oriented for simple shear stresses and a girdle is most likely the result of extensional forces. Multi-maxima pattern have been repeatedly observed in the ablation zone of temperate valley glaciers. This is a clear indication of a more complex stress regime.

Up to today, the COF is analysed under cross-polarised light. The ice grains divert the polarised light according to their orientation. For this measurement, 0.3 mm thin ice core sections need to be cut out from the ice core. This is time consuming and requires some preparation. Furthermore, the valuable ice core needs to be fragmented and these samples are lost for further analyses.

Non-destructive seismic methods can be suitable to support the state-of-the-art fabric analysis. We developed a setup to analyse the COF of ice with ultrasonic measurements. By using point contact transducers, which can easily attached to the ice, we induce a high frequent acoustic wave into the ice and measure the travel times of the signals for different azimuths. With the known ice core diameter and the recorded travel times, we are able to calculate the seismic p-wave velocities for different azimuthal directions and determine the velocity differences as function of azimuth. We show and discuss the resulting velocity variations for such ultrasonic experiments compare them with theoretically derived acoustic velocities from the classical fabric analysis. Here, we found a considerable effect of large grain sizes, which are typically present in temperate ice. The large grain size together with the limited ice core sample size result in unbalanced and not representative measurement statistics. On this basis, we propose further improvements of the methodology.
12.7
Improving the representation of ice cliffs and supraglacial ponds in distributed glacier melt models

Marin Kneib*,**, Evan Miles*, Pascal Buri*, Thomas Shaw*,,**, Michael McCarthy*, Stefan Fugger*,**, Francesca Pellicciotti*,****

*HIMAL group, Swiss Federal Research Institute WSL, 8903 Birmensdorf, Switzerland (marin.kneib@wsl.ch)
**Institute of Environmental Engineering, ETH Zürich, 8049 Zürich, Switzerland
***Advanced Mining Technology Center, Universidad de Chile, Santiago, Chile
****Department of Geography, Northumbria University, NE1 7RU Newcastle, UK

Ice cliffs and supraglacial ponds play a major role in the mass balance of debris-covered glaciers by dramatically enhancing melt, but have only been represented in simplistic ways in distributed glacier melt models by adding a constant melt enhancement to the entire glacier. This representation ignores the dynamics of the ice cliff and pond population, as well as the inter- and intra-annual variability of their distribution and contribution to melt. Physically based melt models of ice cliffs and ponds have been developed at the scale of single features but are currently too computationally expensive to be run over long time-periods for more than a few cliffs or ponds. We have explored two promising avenues to improve the representation of these supraglacial features in distributed melt models. First, we designed two robust and efficient mapping schemes to delineate ice cliffs and ponds from multispectral satellite images. These approaches can be applied to both commercial and freely available, fine (1-5 m) and coarse (up to 10 m) resolution products, and perform overall better than the other existing approaches based on slope, brightness or object based image analysis (Fig. 1). Second, we implemented an automated tracking tool to understand the inter-annual birth and death rates, area changes and backwasting rates of ice cliffs and the filling and draining rates of supraglacial ponds. We ultimately use this data to build a stochastic model to represent the evolution of the cliff and pond population and its total contribution to melt at the glacier scale. This model is computationally efficient and can be easily implemented in future distributed glacier melt models.

Figure 1. Comparison of the cliffs and ponds outlines obtained from the manual delineation (A), Spectral Curvature (B), Linear Spectral Unmixing with scale (C), Adaptive Slope Threshold (D), Simple Slope Threshold (E) and Adaptive Binary Threshold (F) approaches for a section of Bhagirati Kharak glacier (2 m resolution Pléiades scene from September 2018). The values in pink (resp. light blue) correspond to the Dice coefficient of the cliffs (resp. ponds) relative to the manually delineated outlines in this small domain. The background corresponds to the Pléiades false color composite.
12.8
Accessing forest snow cover dynamics in steep mountain terrain using UAV-based Lidar data

Kalliopi Koutantou*, Giulia Mazzotti**, Tobias Jonas** and Philip Brunner*

*Centre for Hydrogeology and Geothermics (CHYN), University of Neuchâtel, Rue Emile Argand 11, CH -2000 Neuchâtel, Switzerland (kalliopi.koutantou@unine.ch)
**WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH- 7260 Davos Dorf, Switzerland

The spatial and temporal dynamics of accumulation and melt of snow under forest canopy is of key interest for hydrology. However, mountain forests in Switzerland are typically located in steep terrain which is difficult to access, particularly during winter. Data concerning snow cover dynamics in mountain forests is therefore limited. Modern remote sensing technology, particularly airborne laser scanning, is a very promising technology for snow depth mapping in such environments. Here we use a YellowScan Mapper II Lidar mounted on a multicopter, for mapping the snow depth in two opposite facing forested slopes in Davos, Switzerland. Consecutive snow-on campaigns took place from December to April 2020 with a high temporal resolution in both slopes, along with snow-off flights early spring. The flights covered a 200*200 m area including dense larch trees forests and forest gaps. A flight plan with interlaced patterns yielded very high point densities. Our validation of the resulting snow maps revealed RMSEs of only ~10cm.

Our data show interesting patterns on the distribution of snow under variable canopy cover, both in terms of small scale physiographic controls and canopy density. Also, the temporal dynamics is fundamentally different between snow cover from the two opposing slopes. Exploratory data analysis shows which factors at which length scale are correlated with the observed snow distribution. Such information can support the development of subgrid parameterizations within coarser-scale snow models.
12.9

Specific mass balance and health of glaciers in High Mountain Asia derived from the continuity equation

Evan Miles*,†, Michael McCarthy*,**, Amaury Dehecq*,***, Marin Kneib*,****, Stefan Fugger*,****, Francesca Pellicciotti*,*****

*Swiss Federal Research Institute WSL, 8906 Birmensdorf, Switzerland
**British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge, UK
***Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich, 8093 Zurich, Switzerland
****Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland
*****Department of Geography, Northumbria University, Newcastle, NE1 7RU, UK
†evan.miles@wsl.ch

Glaciers in High Mountain Asia have experienced intense scientific scrutiny in the past decade due to their hydrological and societal importance. The explosion of freely-available satellite observations has greatly advanced our understanding of their thinning, motion, and overall mass losses, yet our understanding of glacier accumulation and ablation rates is limited to a few individual sites. We combine recent assessments of ice thickness (Farinotti et al., 2019) and surface velocity (Dehecq et al., 2019) within the framework of the continuity equation to adjust observed glacier thinning rates (Brun et al., 2017) for mass redistribution and estimate specific mass balance across the region’s glaciers. We evaluate our results at the glacier scale with field measurements of surface mass balance (35 glaciers sourced from WGMS and individual studies, e.g. Figure 1), then analyze 5527 glaciers comprising 58% of mass for glaciers larger than 2 km².

The specific mass balance results allow us to assess the health of High Mountain Asia’s glaciers for the period 2000-2016 by determining the equilibrium line altitude, accumulation area ratio, committed loss, and ablation balance for each individual glacier. We find that 40% of glaciers accumulate mass over less than 20% of their area (Figure 2). These unhealthy glaciers are concentrated in Nyainqentanglha, whereas accumulation area ratios of 70%-90% are common in the Karakoram and Kunlun Shan regions. We find that surface debris extent explains up to 1000 m of ELA variability, reflecting the importance of avalanching as an accumulation mechanism for debris-covered glaciers.

Overall, 29% +/- 8% of regional ice volume cannot be sustained by current mass inputs, and 35% of glaciers are committed to lose at least half of their volume. In the Ganges-Brahmaputra basin, 41% +/- 6% of ice volume is unsustainable in current climatic conditions. However, we find that the most important and vulnerable glacier-fed river basins (Amu Darya, Indus, Syr Darya, Tarim Interior) are currently supplied with >50% sustainable glacier ablation due to the extensive accumulation areas of the Karakoram Anomaly glaciers. These results provide a comprehensive baseline for the health of the High Asian ice reservoirs in the early 21st Century, and highlight the potential synthesis of distinct remote-sensing observations to understand patterns of recent glacier change.

Figure 1. Continuity-based reconstruction of specific mass balance for Abramov Glacier, showing comparison to WGMS (2019) database of surface mass balance measurements (left), and spatial distribution of specific mass balance (right).
Figure 2. Regional distribution of Accumulation Area Ratios (AARs) for each glacier derived by the continuity approach, along with a histogram of AARs (inset) showing the regional mean (blue) and median (black) values.

REFERENCES
Towards a geoelectrical database for permafrost monitoring to enable the processing and repetition of historical measurements

Coline Mollaret*, Christin Hilbich*, Cécile Pellet* & Christian Hauck*

*Department of Geosciences, University of Fribourg, chemin du Musée 4, CH-1700 Fribourg (coline.mollaret@unifr.ch)

Electrical imaging has been widely applied for permafrost detection and monitoring over different spatial scales. Only very few permafrost sites worldwide are continuously monitored with ERT as part of national monitoring programmes (~10). On the contrary, a much larger number of individual ERT surveys from the past exist (estimated to be >200 alone in the Swiss Alps). These data sets are neither included in a joint database nor have they been analysed in an integrated way. Within a GCOS Switzerland-funded project we address this important historical data source.

In a first step, historical data on permafrost terrain from UniFR groups and their collaborating national and international partners were collected and metadata archived (> 150 profiles). Based on this data collection, we will present a protocol of measurements repetition for summer 2021. Some of the historical measurements were already repeated in summers 2019 and 2020 (e.g. Etzelmüller et al. 2020, Hilbich et al. 2019). The resulting resistivity changes on time scales of 10 to 20 years are presented and analysed according to several sites characteristics such as geomorphology, elevation and surface type. These results are analysed in the context of climate change, showing the value of repeated ERT measurements to detect the climate signal of permafrost change after time spans up to 20 years.

In a second methodological step, the Reproducible Electrical Data Analysis (REDA) scientific Python library (Weigand and Wagner, 2017) will be used for the homogenisation of processed ERT data. It is aimed to reprocess the historical data in an integrative and reproducible manner. Technical challenges for reprocessing a large number of data sets in an integrative way will be discussed. Furthermore, the structure and the ongoing implementation of the international open-access database for ERT surveys is described.

REFERENCES


12.11
Permafrost warming in the Swiss Alps – 20 years of measurement in the framework of PERMOS

Jeannette Noetzli*, Cécile Pellet** & the PERMOS Scientific Committee

*WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, 7260 Davos Dorf (jeannette.noetzli@slf.ch)
**Department of Geosciences, University of Fribourg, Chemin du Musée 4, 1700 Fribourg (cecile.pellet@unifr.ch)

The Swiss permafrost monitoring network PERMOS documents the state and changes of permafrost in the Swiss Alps. It started in the year 2000 as the first national network for long-term permafrost observation. Today it includes the longest and most diverse collection of mountain permafrost data. After 20 years of operation the results based on three main observation elements show a consistent picture of permafrost changes (Figure 1, PERMOS 2019): permafrost is warming, containing less ice but more water, and is flowing faster. The period covers the two decades with the highest air temperatures ever measured in Switzerland and changes were more pronounced in the past decade. Ground ice content and the temporal and spatial snow distribution are the most important factors influencing the change patterns: temperature changes in warm and ice-rich permafrost approaching 0 °C are minimal due to latent heat effects, highest warming rates are measured in cold permafrost in steep bedrock sites at high elevation, and the timing of the snow cover can accelerate or interrupt warming trends.

The PERMOS observation strategy was evaluated repeatedly over the past decades and adapted to new findings and technology. Today, it builds on direct measurements of permafrost temperatures in boreholes, which are complemented by geophysical surveys to detect changes in ground ice content and terrestrial geodetic surveys for the observation of rock glacier creep velocities. These three elements allow for a comprehensive view on permafrost changes. The PERMOS network includes a total of 27 study sites, which are spread throughout the Swiss Alps and are maintained by six academic partner institutions. The network is financially supported by MeteoSwiss in the framework of GCOS Switzerland, the Federal Office for the Environment (FOEN), and the Swiss Academy of Sciences (SCNAT).

All PERMOS data is available open source at the PERMOS Data Portal: http://newshinypermos.geo.uzh.ch/app/DataBrowser/

REFERENCE
Figure 1. Permafrost evolution based on twenty years of measurements in the framework of PERMOS compared to air temperature anomalies based on data from MeteoSwiss.
12.12
Characterising englacial R-channels using artificial moulins

Annegret Pohle*, Mauro A. Werder*,**, Daniel Farinotti*,**

*Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland (apohle@ethz.ch)
**Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland

The theory of channelised en- and subglacial waterflow through so-called R-channels was established by Röthlisberger (1972). This theory has now been widely used for almost 50 years, however, its parameters are still not well constrained. In order to obtain the hydraulic friction parameter and the evolution of the cross-sectional area of an englacial R-channel over time, we conducted experiments in two artificial moulins on Rhonegletscher.

To create artificial moulins we drilled to the glacier bed with a hot water drill and diverted water from a nearby stream down into the boreholes. By installing Conductivity Temperature Depth sensors (CTDs) at different depths in the boreholes and by injecting salt tracers regularly over a time period of two weeks we obtained the hydraulic gradient, the flow speed and the water discharge through the artificial channels. This information then allowed us to compute the cross-sectional area and the hydraulic friction parameter.

This is the first time that the hydraulic friction parameter and the time evolution of the cross-sectional area of an R-channel were directly determined from field experiments. Constraining the parameters of R-channel theory will help improving the predictions of glacial drainage models.

REFERENCES
12.13
Observations of Coherent Backscatter Enhancement in Dry Snow Using Bistatic Radar.

Marcel Stefko*, Silvan Leinss*, Irena Hajnsek*,**

*Institute of Environmental Engineering (IfU), ETH Zürich, 8093 Zürich, Switzerland (stefko@ifu.baug.ethz.ch)
**Microwaves and Radar Institute, German Aerospace Center (DLR), 82234 Wessling, Germany

The coherent backscatter opposition effect (CBOE) is a phenomenon which causes increased backscatter intensity of coherent radiation at small bistatic angles (less than 1 degree) in random disordered media, due to constructive interference of each EM wave scattered in the volume with its time-reversed counterpart. The exact angular width and height of the intensity peak depend on the properties of the incident radiation (wavelength, polarization), the random medium (grain size, mean free path, reflectivity), as well as measurement geometry (local incidence angle, layer thickness). It has been previously investigated in order to better characterize surfaces of various Solar System bodies (Hapke et al. 1998, Black et al. 2001), however it has received comparatively little attention in Earth-focused observations, despite the well known occurrence of significant volume scattering within snow and ice.

In this submission, we report on observation of the intensity peak in a snow layer on top of the peak Rinerhorn in Davos, Switzerland (Figures 1 & 2), using an experimental bistatic, fully-polarimetric, real-aperture, Ku-band radar – KAPRI (Baffelli et al. 2017). We also report on observation of backscatter enhancement in the accumulation zone of Aletsch glacier in space-borne observations with the bistatic synthetic aperture radar mission TanDEM-X.

The measured parameters of the enhancement peak (height, width) can further be connected to physical parameters of the scattering medium. For example, the half-width at half-maximum of the peak can be related to the mean free path between scattering events within the medium (Hapke et al. 1998, eq. 1). Using this model, for KAPRI measurements we can estimate the mean free path within the snow layer to be approx. 53 cm.

We believe that further study of CBOE in the context of Earth-focused observations of snow and ice opens new opportunities for development of quantitative models aiming to derive snow properties from bistatic radar observations.

Figure 1. Bistatic radar backscatter intensity image of Rinerhorn acquired by KAPRI. Map underlay source: Modified Copernicus Sentinel data 2020/Sentinel Hub.
Figure 2. Measured mean backscatter intensity dependence on bistatic baseline between transmitter and receiver (KAPRI data). Range distance to observed area is approx. 3km. In snow, significant enhancement is observed in the co-polarized polarimetric channels in the monostatic direction. Enhancement of smaller magnitude is also observed in the cross-polarized polarimetric channel, and also in forest ROI. All measured intensity values were normalized to the value at 55m baseline.

REFERENCES

12.14
The history of glacier study of the Greater Caucasus and current state of observation

Levan Tielidze*, **

*Antarctic Research Centre, Victoria University of Wellington, P.O. Box 600, 6140, Wellington, New Zealand (tielidzelevan@gmail.com)
**School of Geography, Environment and Earth Sciences, Victoria University of Wellington, P.O. Box 600, 6140, Wellington, New Zealand

The Greater Caucasus is one of the major mountain systems in Eurasia, stretching ~1,300 km from the Black Sea in the west to the Caspian Sea in the east with glaciers covering about 1200 km². As the Greater Caucasus Range is located on the boundary between temperate and subtropical climatic zones, the orientation and height of the range determines the contrasts between the northern and southern macroslopes, with generally larger glaciers in the north than in the south.

In the first part of this work I briefly present the history of the glacier research in the Caucasus Mountains. The second part is more about the current state of glacier observation. I will also present the percentage and quantitative changes in the number and area of Caucasus glaciers over the last half century. Some results of the supra-glacial debris cover assessment will also be provided.

Changes in glacier extent between 1960 and 2014 were determined through analysis of large-scale topographic maps (1:50 000 scale) from several hundreds of aerial photographs taken between 1950-1960 and images from Landsat 8 Operational Land Imager (OLI), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The 30 m resolution ASTER Global DEM (GDEM, 17/11/2011) was used to determine the aspect, slope and height distribution of glaciers.
P 12.1
A ‘subsurface weather station’ to measure boulder-mantle heat fluxes on Murtèl rock glacier


*Alpine Cryosphere Research Group, Université de Fribourg, Chemin du Musée 4, CH-1700 Fribourg (dominik.amschwand@unifr.ch)
**GEOTEST AG, Bernstrasse 165, CH-3052 Zollikofen
***ALPUG GmbH, Richtstattweg 3, CH-7270 Davos-Platz

The debris cover of rock glaciers partially decouples the underlying ice-rich permafrost from the atmosphere, retarding permafrost degradation and making rock glaciers locally important water storages in future deglacierized arid mountain ranges. Heat exchange between atmosphere and permafrost table mainly governs seasonal active layer thawing and long-term permafrost ice melt. However, in the open-framework boulder mantle, heat exchange processes are complex. Numerical modelling and laboratory experiments showed that long-wave radiation between boulders (Lebeau & Konrad, 2016) and convection by air circulation (Wicky & Hauck, 2020) are not negligible with respect to simple conduction.

We attempt to quantify the relative importance of the different energy fluxes by measuring heat-flux components in the boulder mantle of the rock glacier Murtèl (Upper Engadine). This intensively studied rock glacier is an ideal test site because the internal stratigraphy (active-layer thickness, ice content) is known from boreholes and the surface meteorological conditions are continuously measured (Fig. 1, boreholes and meteo station).

We augment the decade-long (surface) meteorological time series and borehole temperature data of the Murtèl rock glacier with a three-part array of sensors:
First, we place microclimate sensors in a natural cavity within the open-framework boulder mantle (Fig. 1, boulder-mantle sensors). They capture conduction in boulders, radiation, and air and moisture flow in the active layer. The upper boundary condition (BC) is resolved by additional sensors for eddy-correlation based turbulent heat flux calculations and sensors for snow-cover characterization (Fig. 1, atmospheric and snow sensors). Ground heat flux from the underlying rock-glacier core (lower BC) is calculated via existing borehole temperature data. Second, this point measurement is complemented with temperature and wind-speed loggers distributed over the rock glacier to capture large-scale air circulation patterns. Time-lapse images in the visible light and thermal infrared ranges monitor seasonal snow-cover and surface temperature evolution (Fig. 1, cameras). Third, hydrological measurements in the rock-glacier forefield consisting of electrical conductivity, water temperature and water column height serve to track water provenance and to estimate discharge (Fig. 1, hydrological sensors).

The project focuses on understanding the temporal evolution of water resources in periglacial catchments and more reliable ice-rich permafrost runoff forecasts. This process understanding will also improve predictions on downwasting rates of debris-covered glaciers.

REFERENCES
Figure 1. Sketch map of the Murtèl rock glacier with existing sensors (meteo station and boreholes) and newly deployed sensors (cameras, hydrological, snow, atmospheric and boulder-mantle sensors).
Unveiling the secrets of the debris cover of the Zmutt Glacier (Valais – CH)

Alessandro Cicoira*, **, James Ferguson*, Inés Dussaillant*, Nico Mölg***, and Andreas Vieli*

*Department of Geography, University of Zurich, Winterturerstr. 190, CH-8057 Zurich (alessandro.cicoira@geo.uzh.ch)
**Department of Geosciences, University of Fribourg, Switzerland
***Department Surface Waters Research & Management, Eawag, Switzerland

Supraglacial debris strongly influences the morphology, dynamics and mass balance of debris-covered glaciers. When debris-laden ice melts, a surface debris layer is left behind which insulates the glacier and thereby reduces the ablation rate. Therefore, a better understanding of the processes controlling the evolution of debris-covered glaciers and their mass balance requires detailed information about the debris cover (Mölg et al., 2019).

For this purpose, we investigated the debris cover and the energy balance of the Zmutt Glacier (Valais - CH) by means of in-situ and remotely sensed observations. During two field campaigns in summer 2020, we surveyed a small area on the glacier characterized by large spatial variability in debris thickness. We performed nine repeated flights with an unmanned aerial vehicle equipped with an infrared sensor under different weather and radiation conditions at different times of the day. The resulting temperature maps are constrained by calibration measurements of ground surface temperature within the debris cover and at the location of supraglacial water ponds.

Additionally, two meteorological stations monitoring liquid precipitation, wind speed and direction, short and long wave radiation (incoming and outgoing) as well as air temperature have been installed on the glacier tongue; one within the surveyed area and the other one two hundred meters of elevation lower. On the basis of this unique dataset, a numerical inversion of the thermal imagery using energy mass balance modelling allows to recover the debris thickness over the surveyed area. The modelling is validated by comparing the calculated values with numerous direct measurements performed in the field.

First results from this method are promising, showing a clear relationship between the temperature field and corresponding debris thickness inversion. Further work is required to quantify the uncertainties due to spatial inhomogeneities and to better understand process feedbacks.

REFERENCES
P12.3
Impact of debris cover on future evolution of HMA glaciers


* Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland.
** Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland.
*** Department of Geoscience and Remote Sensing, Delft University of Technology, Netherlands.
**** Laboratoire de Glaciologie, Université libre de Bruxelles, Belgium.
***** Department of Geosciences, University of Fribourg, Fribourg, Switzerland.

Knowing the future evolution with accuracy of glaciers is extremely important, so that appropriate measures can be taken to mitigate negative impacts on sea level change, hydropower production and water availability. However, to date, the majority of regional- to global-scale glacier models (Marzeion et al., 2020) do not explicitly model ice flow, do not take debris cover evolution into account, and were not forced with the latest climate projections from the Model Intercomparison Project Phase 6 (CMIP6).

In this study, we extend the capability of GloGEMflow – a combined mass-balance ice-flow model (Zekollari et al., 2019) – with a newly developed debris evolution component, and applied it to all glaciers in High Mountain Asia (HMA). The model was initialized with the ERA5 re-analysis product, while the future forcing was provided by CMIP6 climate projections. The model was calibrated with glacier specific geodetic volume changes covering more than 98% of HMA's glaciers (Hugonnet et al., in review). Contemporary debris cover was classified using Landsat scenes, and debris thickness was determined by using an energy-balance model to constrain altitudinal Ostrem curves, combined with sub-debris specific mass balance estimated through the continuity equation. In GloGEMflow, debris cover and its thickness evolve in the future as a function of mass balance and ELA change, and are calibrated through satellite observations spanning the last 30 years.

First results from model runs with and without the debris-evolution component showed significant discrepancy in the projected future glacier evolution. Indeed, the reduced (enhanced) ice melt beneath debris thicker (thinner) than a few centimeters, does not only impact the local mass balance (Fig. 1c, 1d) and therefore the future glacier geometry (Fig. 1a, 1b), but also the total future volume evolution. Constraining debris accumulation on glaciers is key to understand future glacier evolution.
Figure 1. Future evolution of Langtang Glacier in scenarios (a) with debris cover and (b) without debris cover. Panels (c) and (d) show the corresponding mass balance evolution. The red highlighted surface lines in (a) and (b) show how the glacier geometry evolves differently.

REFERENCES
P 12.4
Nonlinear feedbacks driving pattern formation on debris-covered glaciers

James Ferguson1, Alessandro Cicoira1,2, Inés Dussaillant1, Nico Mölg3, and Andreas Vieli1

1 Department of Geography, University of Zurich, Winterthurerstr. 190, CH-8057 Zurich (james.ferguson@geo.uzh.ch)
2 Department of Geosciences, University of Fribourg, Switzerland
3 Department Surface Waters Research & Management, Eawag, Switzerland

Debris-covered glaciers are commonly found in most glaciated regions of the world. When debris mixes with the ice in the accumulation zone, primarily due to avalanching, it eventually melts out in the ablation zone and remains on the surface of the glacier where it reduces the surface melt rate once it becomes thick enough. The mean debris layer thickness increases down-glacier but the local surface morphology tends to be highly irregular and typically exhibits a range of patterns from individual humps to lengthy medial moraines.

In this study, we examine the evolution of surface patterning on debris-covered glaciers by developing a numerical model that captures the coupled effects of ice transport, debris transport, melt out, debris redistribution due to topographical effects, and shading effects due to feedbacks between aspect and surface roughness. We perform a sensitivity analysis to determine which feedbacks are most important for surface pattern evolution and we compare our model results with field observations from Zmuttgletscher, Valais.
P 12.5

Rescue, documentation and re-analysis of Swiss glacier monitoring data

Claudia Kurzböck*,**, Lea Geibel*, Matthias Huss*,** & Andreas Bauder*

*Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Hönggerbergring 26, CH-8093 Zurich (ckurzboeck@ethz.ch)
**Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Zürcherstrasse 111, CH-8903 Birmensdorf

Long-term glacier monitoring in Switzerland has resulted in some of the longest and most complete data series globally. Point mass balance observations, starting in the 19th century, are the backbone of the monitoring as they represent the raw and original data demonstrating the response of surface accumulation and melt to changes in climate forcing. However, little attention has so far been devoted to the careful documentation of the raw point mass balance measurements, including an assessment of their sources and an estimate of their quality. Yet accurate metadata are highly important for homogenisation of the in-situ measurements and subsequent analysis of the long-term series.

For compiling and documenting raw point mass balance data acquired in Switzerland, a complete re-assessment of all measurements from pre-existing digital sources, published reports, unpublished documents, field notes, as well as meta-knowledge of the observers has been performed. A newly developed system of indicators allows attributing quality measures and further information on data acquisition, sources and observers for single measurements. At this stage, data series for about 60 individual glaciers are available, corresponding to almost 60,000 point observations. The data comprise three types of point measurements: 55 series of annual mass balance, 46 series for winter snow accumulation, and 46 series with intermediate observations (daily to sub-seasonal). All previously available point mass balance observations have been re-assessed and documented, but a significant amount of additional data has been discovered and digitized summing up to 68 new data series, adding more than 20,000 point measurements.

Many of the previous observations were not traceable, and their quality was mostly unknown. The quality-checked and updated original data permits the re-analysis of consistent time series of glacier-wide mass balance allowing further interpretation of the climate change impacts on Swiss glaciers.

Figure 1. Coverage of annual point mass balance data series in Switzerland. The size of the dots and their colour indicate the length of the observational period. Important sites are labelled.
Figure 2. Number of glaciers with annual and winter point mass balance observations between 1884 and 2020 averaged in 5-year periods.
P 12.6
Using age-layer modelling for interpreting borehole age-profiles of rock glaciers

Gwendolyn Leysinger Vieli*, Andreas Vieli* & Alessandro Cicoira*

*Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Basel
(gwendolyn.leyssinger@geo.uzh.ch)

The genesis of rock glaciers differs fundamentally from ‘normal’ glaciers and results in much older landforms that are often reaching ages of several millennia. Recent datings of rock glacier material from boreholes indicate early Holocene ages for rock glaciers and allow the derivation of age-depth profiles at the borehole location. We use here a 2-dimensional numerical modelling approach that calculates age-layers (isochrones) within the rock glacier body and that considers the accretion, melt and flow-advection of rock glacier material. We apply this model to the case of Lazaun rock glacier (Southern Ötztal Alps) for which a well dated profile from a borehole exists, with ages at the bottom older than 9000 years (Krainer et al. 2015). With our modelling we are able to reproduce the observed age-depth profiles well and are able to infer a long-term accumulation rate that is around 1 cm/yr which is an order of magnitude higher than a previous estimate that does not account for deformation. The modelling is further consistent with the classic rock glacier genesis of material accretion in the upstream talus slope and confirms the dominance of deformation in the shear-zone at the bottom layer of the rock glacier. We conclude that combining age-layer modelling with dated depth-profiles of rock glaciers allows for important new insights into our understanding of rock glacier evolution and dynamics.

REFERENCES

P 12.7
Multispectral and thermal mapping of the polythermal Gorner-/Grenzgletscher terminus

Martin Lüthi*, Michael Thalmann*, Sebastiano Rusca**, Alessandro Ciccoira* & Nico Mölg*

*Department of Geography, University of Zurich, 8057 Zurich (martin.luethi@geo.uzh.ch)
**ETH Zurich, Autonomous Systems Laboratory (ASL), Zurich, Switzerland

Gorner-/Grenzgletscher is the only large polythermal glacier of the Alps. Even in the terminus area at 2500 m a.s.l. the glacier ice is at subfreezing temperatures, with cold ice discernible by its bright white color. The impermeable cold ice leads to the formation of deeply incised streams and lakes on the glacier surface which are unique in the Alps.

With drones carrying thermal, multispectral and optical cameras, we mapped structures on the ice surface. These thermal images reveal an intricate pattern of high- and low-emission areas on the glacier surface, linked to streams, lakes, water-filled cyroconite holes within the ice, and further patterns that are not easily attributable to surface features. First results of the analysis of these images with neural-network based classification algorithms elucidate several classes ice properties with different characteristics.
The snow microstructure on sea ice - first results from the MOSAiC expedition

Amy Macfarlane*, David Wagner*,**, Ruzica Dadic**, Stefan Hämmerle***, Martin Schneebeli*

*WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland (macfarlane@slf.ch)
**Victoria University of Wellington, Antarctic Research Centre, New Zealand
***Scanco Medical AG, Basserdorf, Switzerland
****CRYOS, EPFL, Lausanne, Switzerland

Snow on sea ice governs much of the heat exchange during winter, and its melting during summer. The microstructure has a key role in the thermal heat resistance and in the albedo. We installed a micro-CT on board of the research icebreaker Polarstern during the MOSAiC-expedition. The MOSAiC expedition drifted for a full year in the Arctic Ocean. We could measure every week 1-2 full snow profiles between 0.1-0.3 m deep. We extracted, mostly in-situ, cores of 48-78 mm diameter and of about 0.1 m length, and scanned with 18-28 µm resolution. The goal of these measurements was to understand the formation and metamorphosis of the snowpack in detail, and to derive detailed geometrical and physical properties from the samples. We will present first examples and overview of characteristic snow profiles from leg 1 - 4, spanning the winter, spring and melt season, and the evolution of the sea ice from solid ice towards the formation of the surface scattering layer, a snow-like ice cover. We could also observe the inclusion of brine in some snow samples, especially in first year ice. Until know it was not known how brine is included in the ice structure of snow.
P 12.9

Swiss-wide post-Little Ice Age glacial lake evolution


*Department Surface Waters – Research and Management, Eawag, Swiss Federal Institute of Aquatic Science and Technology, Seestrasse 79, CH-6097 Kastanienbaum (nico.moelg@eawag.ch)
** Geography Department, University of Zurich, Winterthurerstrasse 190, CH-8057 Zürich
***Hydrology Division, Swiss Federal Office for the Environment FOEN, Papiermühlenstrasse 172, CH-3063 Ittigen

During the currently accelerating glacier retreat, number and size of glacial lakes in most mountain regions of the world are rising. Knowledge about the location and size of new (post-Little Ice Age, LIA) glacial lakes allows (1) analysing their environmental conditions to better understand formation processes, and (2) deriving information regarding their hazard potential.

In this study we present the first complete multi-temporal glacial lake inventory for Switzerland spanning ~the end of the LIA to present. The availability of historical orthophoto mosaics, existing lake boundaries for the 2000s and 2010s (Swisstopo TLM3D), and glacier boundaries from the end of the Little Ice Age (LIA, ~1850s) and several dates thereafter, facilitated the generation of a time series of glacial lake datasets for seven points in time between the end of the LIA and 2016.

Altogether 1276 natural glacial lakes formed in this period, 1212 still existing in 2016, with a total area of 6.5 km² (Figure 1). The lakes are homogeneously distributed over the deglaciated terrain without a clear spatial hotspot, but are predominantly in the most glaciated Cantons of Valais (2.8 km²), Graubuenden (1.8 km²), and Bern (1.3 km²). Periods of strong lake area/number increase alternate with periods of attenuated increase, corresponding well with the temperature evolution that strongly drives glacier changes. We also extracted several parameters relevant for lake hazard assessment, e.g. dam material and topographic potential.

In a next step we want to discuss lake monitoring and management strategies, also with regard to a future with a continuously increasing number of lakes located inmidst of a geomorphologically young, dynamic and unstable alpine environment.

Figure 1. Distribution of glacial lakes over the Swiss Alps.
P 12.10
A framework for modelling rock glaciers and permafrost at the basin-scale in high Alpine catchments

Luisa Pruessner*,**, Matthias Huss*,*** & Daniel Farinotti*,**

*Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland
(pruessner@vaw.baug.ethz.ch)
**Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland
***Department of Geosciences, University of Fribourg, Fribourg, Switzerland

Water stores in rock glaciers may become important water reservoirs in future, since rock glaciers are thought to be more resilient to climate change than clean-ice glaciers (Brighenti et al. 2019). In particular, regions which currently rely on glacial runoff may need to find alternative water resources. In order to project future runoff potential from rock glaciers, distributed runoff models suitable for high Alpine catchments are needed.

In this work, the distributed Glacier Evolution and Runoff Model (GERM; Huss et al., 2008; Farinotti et al., 2012) is extended by a permafrost module, which allows for the modelling of rock glaciers in Alpine catchments. The permafrost module treats permafrost as discrete depth layers in a one-dimensional column for all grid cells. Thermal properties are calculated from the layer’s constituents (ice, water, air and solid component). The temperature evolution is computed using heat conduction and latent heat exchanges, modified by ventilation effects. The contribution the the runoff is inferred from permafrost degradation.

First results for the Schafberg catchment are presented here.

Figure 1. Annual modelled runoff at Schafberg. Total runoff is summed over all catchment grid cells and the runoff contribution from permafrost is also summed over all depths and grid cells containing permafrost.

REFERENCES


P 12.11
Challenges of estimating the snow-rain transition zone in the semi-arid Andes

Simone Schauwecker*, Gabriel Palma*, Shelley MacDonell* & Katerina Goubanova*

*CEAZA (Centro de Estudios Avanzados en Zonas Áridas), La Serena, Chile  (simone.schauwecker@ceaza.cl)

The height of the snow-rain transition, closely related to the 0°C-isotherm, is a crucial variable for snow cover extent and natural hazards. In semi-arid northern Chile, it plays a fundamental role in high discharge flows. A high snow-rain transition above 3000 m leads to a strong increase in the pluvial area of Andean basins (Garreaud, 2013). Estimations of past and future changes in the snow/rain transition zone and its relation to large-scale climate oscillations, such as El-Niño Southern Oscillation (ENSO) are therefore fundamental for water availability assessment and adaptation strategies and might eventually serve to develop landslide, debris flow and mudflow early warning systems in this region (Vergara del Pont, 2018; Palma, 2019). However, there are important challenges that hinder the assessment of the snow-rain transition zone in semi-arid environments and little is known about future changes under different global warming scenarios. For example, it is difficult to identify statistically significant trends for the snow-rain transition in a region where on average 90% of the precipitation depends on five or fewer events per year. Additionally, most weather stations in the Andes are located in valley bottoms, influenced by local conditions and the assumption of free-air temperature lapse rates contributes to the uncertainty. Also, satellite observations (e.g. bright band information) are limited over mountainous areas.

The main questions driving our work are therefore:

i) What is the elevation band of the snow-rain transition zone for the past decades (1979-2020)?
ii) What is the role of large-scale climate modes such as ENSO and PDO in the interannual and interdecadal variability of the snow-rain transition height?

We combine different data sets to estimate the past snow-rain transition zone the semi-arid Chilean Andes. Meteorological station data are used to vertically extrapolate temperature with free-atmosphere lapse rates. Results are then compared to radiosonde records, MODIS snow cover products, ERA5 atmospheric reanalysis, and a Regional Climate Model (Aladin-Climate, 12km resolution, 1979-2018). First results from radiosonde data indicate a relationship between the snow-rain transition height and ENSO and PDO variability. The new findings will enable us to model future spatially-distributed precipitation phase probabilities along the semi-arid Andes.

Figure 1. Map of the Elqui River catchment. A rise of the snow-rain transition altitude leads to an important increase of the pluvial area for many large foothill catchments along the Andes – increasing the risk for natural hazards.

REFERENCES
Palma, G. 2019: Análisis y cartografía de procesos geológicos peligrosos en Vicuña, Región de Coquimbo, Chile
P 12.12
Calving styles and patterns vary strongly for different front geometries

Andrea Walter*,**, Martin P. Lüthi*, Martin Funk**, Andreas Vieli*

*Department of Geography, University of Zurich, Winterthurerstr. 190, 8057 Zürich
(andrea.walter@geo.uzh.ch)
**ETH Zürich, VAW, Hönggerberg 26, 8093 Zürich

Glacier calving is an important process for the mass loss of tidewater outlet glaciers in Greenland. At the same time the calving process causes significant uncertainties in currently used glacier flow models and thus projections of the future evolution of the Greenland glaciers and ice sheet. These uncertainties are also due to a lack of observations. This study contributes with a very detailed and unique dataset of calving activity and front characteristics to fill this gap.

Two tidewater outlet glaciers in Greenland, Eqip Sermia and Bowdoin Glacier, were observed during six and two field campaigns, respectively, with a terrestrial radar interferometer (TRI). From the TRI measurements the ice flow field, the front position, crevasse patterns, strain rates and calving activity were extracted. Since the two glaciers are characterised by different geometries and velocity fields, the influence of those parameters on the calving process is investigated. The results highlight that both glaciers show highly variable calving activities along the front and over time. The calving style also differs significantly between the individual front geometries. At Bowdoin glacier the mass loss is dominated by a few large-scale calving events, while Eqip Sermia is characterised by frequent smaller events and for the front section ending in deeper water subaqueous mass loss. In a further step we use this unique dataset to investigate the driving forces on the calving process and the comparison with results from state-of-the-art calving models. This will allow us to understand the suitability of different calving implementations in the models and to optimise parameters to better reproduce the observed calving rates.
The Role of Local Resolution Weighting in Automatic Avalanche Mapping with Sentinel-1

Cedric Tompkin*, Silvan Leinss*

*Chair of Earth Observation and Remote Sensing, ETH Zurich, Leopold-Ruzicka-Weg 4, Zürich 8093

The documentation and statistical analysis of snow avalanche events is an important factor to improve avalanche predictions. So far, reports are based on human observations and therefore are sparse in bad weather conditions or remote areas. Sentinel-1 (S1) synthetic aperture radar (SAR) images provide a weather-independent coverage of the Swiss Alps all six days and have proven to be an effective basis for detecting avalanche deposition zones by experts. The manual mapping of avalanches on pixel level (here called segmentation) is extremely laborious, which makes an automation indispensable. The steep terrain of the Swiss Alps combined with the slant view angle of the SAR complicate this process. In areas of layover and shadow, avalanches are not visible and the spatial resolution varies strongly with the local radar incidence angle.

Local resolution weighting (LRW) merges images of different satellite orbits by weighting them by their local spatial resolution. This creates an image of very extensive coverage and overall high spatial resolution with only little loss of temporal resolution. We present a processing pipeline which automatically downloads, processes and merges S1 images with LRW before segmenting the avalanches with a deep neural U-Net from a backscatter difference image. We created a dataset of 914 manually drawn avalanche outlines from the 4th of January 2018. It was used to evaluate the avalanche backscatter characteristics with respect to the incidence angle and the polarization, to quantify the effect of merging images with LRW on the brightness and segmentation of avalanches and to train and test the U-Net.

We show that avalanches appear brighter when imaged with a large local radar incidence angle. This motivates the use of LRW as it weights these parts stronger. Furthermore, the merging of images with LRW has proven to be very beneficial to a segmentation with a threshold. Our preprocessing pipeline with LRW followed by a segmentation with our U-Net achieved high precision, recall and F1 scores of 0.88, 0.76 and 0.81.

An automatic avalanche mapping in the Swiss Alps on the 4th of January is demonstrably feasible with a good accuracy. LRW and deep learning proved to be promising approaches to this task and especially deep learning techniques should further be developed. It remains to be studied to what extent our results can be generalized to other events with different snow conditions and avalanche visibility.
Modelling the long-term mass balance and firn evolution of Abramov glacier, Pamir Alay

Marlene Kronenberg*, Horst Machguth*, Ward van Pelt**, Eric Pohl* & Martin Hoelzle*

*Department of Geosciences, University of Fribourg, Chemin de Musée 4, CH-1700 Fribourg (marlene.kronenberg@unifr.ch)
**Department of Earth Sciences, Uppsala University, Uppsala, Sweden

Glaciers located in Western High Mountain Asia have shown mass gain or limited mass losses compared to other mountain regions since 2000 (e.g. Brun et al. 2017; Shean et al. 2020). The reasons for this behaviour have not yet been satisfyingly resolved. An increase in accumulation is considered a potential cause for this situation. However, meteorological as well as glaciological in situ data are limited for the region impeding an analysis over longer periods. In this context, modelling energy and mass fluxes can enhance our understanding.

A distributed energy balance model coupled to a multi-layer firn model EBFM (van Pelt et al. 2012, 2019) is applied to study the mass balance evolution for a glacier in the region for which unique in situ data are available (Fig.1). Abramov glacier is located in the Pamir Alay at the northern margin of regions with anomalous mass balance behaviours. In a first step, we run the EBFM with meteorological in situ measurements from a weather station located next to the glacier for the period from 1967-99. Second, we use measurements from an automatic weather station installed in 2011 to run the model. In a third step, we evaluate gridded meteorological data products. Those products are then used to run the EBFM for periods without in situ measurements. Model parameters are calibrated with a subset of the mass balance point measurements available for the periods of 1969-99 (174 points, monthly resolution) and 2011 to present (20 points, annual resolution). Another subset of the mass balance point measurements as well as firn data from the 1970s and 2018 are used for model validation.
P 12.15
CRAMPON - a workflow for obtaining and assimilating near real-time glacier mass balance observations

Johannes Marian Landmann*,**, Hans Rudolf Künsch***, Matthias Huss*,**,****, Christophe Ogier*,** & Daniel Farinotti*,**

*Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), Swiss Federal Institute of Technology (ETH), Hönggerbergring 26, CH-8093 Zürich (landmann@vaw.baug.ethz.ch)
**Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft (WSL), Zürcherstrasse 111, CH-8903 Birmensdorf
***Seminar for Statistics, ETH Zurich, Zurich, Switzerland
****Département des Géosciences, Université de Fribourg, Chemin du Musée 4, CH-1700 Fribourg

Switzerland is affected by shrinking glaciers in many ways, but the decrease in summer runoff from glaciers might be the most important one. This runoff decrease impacts the available water volume downstream of glaciers and thus reduces both drinking water availability and the possibility to produce electricity. This is why interest in the near real-time status of glacier mass balance is high. During the hot summer months, when public interest is highest, there are often no in situ mass balance observations available though. This makes it impossible to make accurate statements about the current state of a glacier. To tackle this issue, we have initiated CRAMPON – Cryospheric Monitoring and Prediction Online. In CRAMPON, we aim at two things: first, we want to reduce near real-time mass balance uncertainty by ensemble modelling with frequent assimilation of remote and in situ observations. The former are satellite acquisitions, for the latter we rely on automated camera observations. Second, we want to make the obtained near real-time mass balance available to the public on a web platform.

To establish frequent in situ observations, we mounted up to nine autonomous cameras on four Swiss glaciers during the summer ablation periods of 2019 and 2020: Rhonegletscher, Findelengletscher, Glacier de la Plaine Morte, and Aletschgletscher (see Fig. 1). These cameras take images of suitably-marked ablation stakes every 20 minutes, which allows aggregating the readings to daily mass balance estimates. Remote observations stem from Sentinel-2 acquisitions and comprise broadband albedo and derived snow lines. They are not as frequent as the camera observations (potential availability: every 2-3 days), but have a better spatial coverage. We assimilate these estimates in an ensemble of three temperature index melt models and one simplified energy balance melt model (Hock, 2003, for an overview). This model ensemble is driven with gridded uncertain meteorological input and uncertain parameters, since it should be run over all Switzerland in a next step. To perform the assimilation, we use a particle filter (Van Leeuwen et al., 2019, for an overview). Particle filters are flexible data assimilation methods that do not constrain the models and distributions used to linearity or Gaussianity. By adding a custom resampling method to the filter, we ensure that every model is always maintained in the ensemble, and that temporarily poorly performing models can recover at a later stage. This makes it possible to analyze model performance and parameter distributions over time.

The validation of the operational ensemble shows that the mass balance analysis follows the observations closely (Continuous Ranked Probability Score within 1cm of the stake reading on average) and can well reproduce also independent measurements. A cross-validation experiment between the glaciers with camera observations shows that the ensemble does not deviate more than 7% from the observed cumulative mass balance. A comparison to the autumn glacier-wide mass balance provided by the Glacier Monitoring Switzerland (GLAMOS; www.glamos.ch) initiative shows agreement within few centimeters, except for Findelengletscher, where the camera locations might not be representative for the entire glacier mass balance. In general, over 95% of the uncertainty in the cumulative ensemble mass balance stems from the period before summer observations are available. This shows that it is advantageous to start with observations as early as possible in the season.

Our contribution will provide insights into the processing pipelines, highlight the importance of frequent in situ and remote observations for near real-time glacier mass balance estimation, and present the status quo of the CRAMPON online platform.
REFERENCES
P 12.16
Understanding monsoon controls on the energy- and mass-balance of glaciers in High Mountain Asia

Stefan Fugger1,2, Michael McCarthy1, Catriona Fyffe1,3, Evan Miles1, Simone Fatchi4, Marin Kneib1,2, Wei Yang5, Patrick Wagnon6, Francesca Pellicciotti1,3

1Swiss Federal Research Institute WSL, 8906 Birmensdorf, Switzerland
2Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland
3Department of Geography, Northumbria University, Newcastle, NE1 7RU, UK
4Department of Civil and Environmental Engineering, NU Singapore, SG
5Institute of Tibetan Plateau Research, Chinese Academy of Sciences, CN
6Univ. Grenoble Alpes, CNRS, IRD, Grenoble-INP, IGE, 38000 Grenoble, France

The South- and East-Asian Monsoons (AMs) shape the melt and accumulation patterns of glaciers in large parts of High Mountain Asia (HMA) in complex ways (Maussion et.al, 2014) due to the interaction of persistent cloud-cover, large temperature amplitudes, high atmospheric water content and high precipitation rates. While the AMs dominate in the southern and eastern regions, they progressively lose influence westward towards the Karakoram, where the influence of westerlies is predominant (Figure 1) (Yao et.al, 2012).

Previous applications of energy- and mass-balance models for glaciers in HMA have been limited to single study sites (e.g. in Khumbu, Langtang and Parlung) and a few attempted to link model results to large-scale weather patterns (Mölg et.al, 2013). While these studies have helped to understand glacier melt and accumulation in HMA under specific local climates, a regional perspective is still missing. In this study, we use a full energy- and mass-balance model together with eight on-glacier AWS datasets around HMA to investigate how AMs conditions influence the glacier-surface energy- and mass-balance. In particular, we look at how debris-covered and debris-free glaciers respond differently to the AMs, validating our results against independent in-situ measurements.

We identify combined effects of the AMs and debris-cover on the glacier mass-balance (Figure 2), seek for explanations in the surface energy-balance and discuss regional differences. We also discuss the important role of high-elevation monsoonal snow in controlling accumulation and ablation in HMA. This work is fundamental to the understanding of the present and future HMA cryosphere and water budget evolution and will inform long-term studies on HMA catchment hydrology.

Figure 1. Study sites and large scale weather patterns
Figure 2. Seven-day sums of ice- and snow-melt at AWS sites on debris covered glaciers. Dashed lines indicate theoretical melt regime if there was neither monsoon, nor debris or snow cover.

REFERENCES
P 12.17
The thermal behaviour of a low elevation cold talus slope: Insights through numerical modeling

Jonas Wicky*, Christian Hauck*

*Department of Geosciences, University of Fribourg, Chemin du Musée 4, 1700 Fribourg (jonas.wicky@unifr.ch)

Coarse blocky talus slopes are a characteristic geomorphic feature of the alpine high mountains, but can also be found at lower elevations. Their high permeability allows for air circulation within the ground leading to an increase in convective heat transfer. The convective heat transfer related to air, especially the seasonal cycle of natural convection, is known to have a cooling effect on the ground (Wicky and Hauck, 2020). At low elevations, this can lead to the occurrence of azonal permafrost (Morard et al., 2012). Dreveneuse, a well-studied former PERMOS site, is located at 1500 m a.s.l. and showed continuous subzero temperatures for some years (PERMOS, 2016). Research at Dreveneuse has already been done conducting ample field measurements (Morard et al., 2012) and geophysical monitoring (Mollaret et al., 2019), whereby the geophysical data are still ambiguous concerning the ground ice content. We try to analyze and re-model ground temperature measurements of the Dreveneuse low elevation talus slope in the Western Swiss Alps in order to understand to what extent convection is the explaining factor for the observed thermal anomalies. The 2D model is set up in COMSOL Multiphysics and solves for heat conduction coupled with a Darcy approach for the convective air flow within the ground (Wicky and Hauck, 2020) and is driven by temperature data measured on site.

REFERENCES