

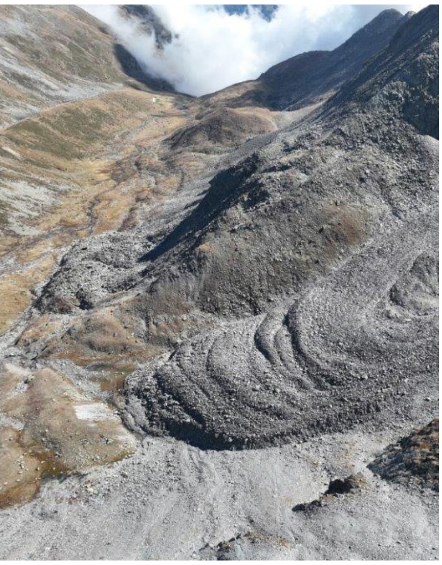
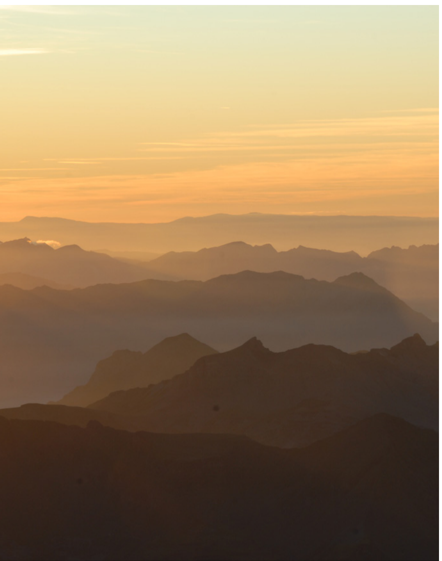

Abstract Collection

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15th DACH Permafrost Conference

8–10 January 2025, Davos, Switzerland

WSL Institute for Snow and Avalanche Research SLF

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Cover photos

Top down:

1. Matterhorn Hörnligrat, Switzerland (Samuel Weber)
2. Kotzebue Expedition 2024, Alaska (Jens Strauss)
3. Jungtal Rock Glacier, Switzerland (Willy Gitz)
4. Vista Jungfraujoch, Switzerland (Samuel Weber)

How to cite

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Preface

The *DACH Permafrost Union* (http://dach-permafrost-union.org/) provides a forum for scientists from the DACH (Germany, Austria, and Switzerland) and neighboring countries working in polar and mountainous permafrost regions. The main objective is to exploit synergies and jointly develop methodological approaches. The *DACH Permafrost Conference* is an annual meeting and is its most essential platform for promoting direct exchange between researchers.

The Permafrost Research Group at the WSL Institute for Snow and Avalanche Research SLF is delighted to host the 15th DACH Permafrost Conference in Davos in January 2025, thereby supporting any collaboration in this interdisciplinary spectrum and promoting exchange between people from different countries and in different career stages (students, PhD candidates, postdocs, researchers, and professors). We counted 91 registrations with 33 young scientists and received 76 contributions.

A big thank you for the financial support by SEP (Swiss Snow, Ice and Permafrost Society), SLF (WSL Institute for Snow and Avalanche Research SLF), and DGP (German Society of Polar Research) as well as to the following persons who contributed essentially to the organization and realization of the conference, the PYRN workshop, GTN-P meeting, and the SLF special tour as well as to the critical assessment of the contributions: A. Bast, Y. Bühler, I. Enescu, F. Felder, J. Gaume, C. Hänni, I. Hartmeyer, M. Heggli, M. Hofmänner-Berner, A. Irrgang, M. Lichtenegger, C. Lucas, J. Nötzli, M. Oberhänsli, R. Pal, E. Peruselli, M. Phillips, L. Pierhöfer, S. Saladin, N. Salzmann, S. Senn-Raschle, J. Strauss, Ch. Suter, M. Ulrich-Nath, and B. Walter.

Davos, January 2025

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Monitoring of permafrost dynamics using electrical resistivity tomography (ERT) at the Aiguille du Midi in the French Alps

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Keywords: electrical resistivity tomography, ERT, permafrost, Aiguille du Midi

Permafrost in high mountain environments is highly sensitive to climatic variations, impacting both landscape stability and hydrological systems. Electrical resistivity tomography (ERT) measurements could provide detailed information on subsurface conditions, revealing changes in resistivity that correlate with variations in lithology, ice content, temperature, or/and moisture. In this study, ERT monitoring has been conducted over a four-year period (2020–2023) to explore the distribution and evolution of permafrost at The Aiguille du Midi (located on the NW side of the Mont-Blanc massif) in the French Alps. A total of 3 cables of 32 take-outs each, 5 m spacing (thus 155 m long), were installed. They were deployed downwards from the summit in three directions (north, south, and east face). However, with the extreme climatic conditions at this altitude, ERT measurements run into many problems (high contact resistance, cables cut off because of lightning). Time-laps inversion of ERT measurements collected at different elapsed times was carried out. The resistivity distribution shows parts of the internal structure (galleries, elevator), fractures as well as seasonal and annual variations of the active layer. A petrophysical analysis in the laboratory on a rock sample taken from the site was carried out to evaluate the thermal dependence of electrical resistivity in a saturated condition. A petrophysical model describing the thermal dependency of resistivity was used to connect ERT measurements to temperature in field conditions. Temperature distribution estimated from ERT was compared to the temperature measured in the borehole on-site. A good correlation could be noticed between temperature estimated from ERT and that measured on-site in summer when data quality is good enough. However, poor data quality leads to errors in temperature estimation in winter. This research demonstrates the effectiveness of ERT as a tool for long-term monitoring, evaluation of permafrost thermal conditions, and hydrological dynamics in alpine environments.

Testing time-lapse gravimetry on Murtèl rock glacier (Upper Engadine) to spatially resolve subsurface water/ice storage changes

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Keywords: mountain permafrost, time-lapse gravimetry, groundwater, permafrost hydrogeology

Seasonal storage of liquid and frozen water in high-mountain catchments will play an increasingly important role as a hydrological buffer in rapidly deglaciating mountains, sustaining streamflow during late-summer dry phases after completion of the snowmelt. Depending on the local topo-climatic conditions, these catchments can be (partly) underlain by permafrost. However, below-ground water pathways and water/ice storage changes are currently poorly characterized in high-mountain catchments because field data with sufficient resolution to capture spatial variability are sparse. Among geophysical techniques, time-lapse gravimetry stands out as a method that is directly sensitive to the target quantity and mass (density) distribution changes at an appropriate spatial scale. Time-lapse gravimetric surveys have successfully quantified groundwater storage changes in high-mountain catchments but have never been deployed on mountain permafrost, notably rock glaciers.

33 years after pioneering gravimetric investigation on Murtèl rock glacier (D. Vonder Mühll & E. Klingelé), we return to the site with a state-of-the-art relative spring gravimeter (Scintrex CG-6 Autograv) able to resolve water/ice storage changes at the few µGal range (corresponding to <10 cm water equivalent). First, we present results from repeat gravimetric surveys, complemented by drone-based photogrammetry, that we carried out in early and late Summer 2024. We observed significant, spatially variable gravity changes attributable to the seasonal ice loss in the coarse-blocky active layer. These changes were hinted at on the point scale by subsurface stake measurements and energy budget calculations. Second, we compare our data with the 1991 data. Finally, we discuss the strengths and limitations of time-lapse gravimetry in complex mountain permafrost terrain, including challenges related to the decomposition of the temporal gravity signal to different water and rock mass distribution changes.

Geoelectrical insights on the evolution of permafrost in post-glacially uplifted marine deposits on Svalbard

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Keywords: permafrost, salt, cryopeg, Svalbard, Ny-Ålesund, electrical resistivity, marine deposit

Saline permafrost is primarily found in marine deposits beneath shallow shelf seas and can extend several kilometers inland from the present Arctic coastlines. On land, it forms when previously submerged marine sediments are exposed to the atmosphere, either due to sea level regression or post-glacial rebound. In Svalbard, northwest of Ny-Ålesund, the Kvadehuksletta region features a complex landscape of raised beach terraces, lagoons, paleo-lagoons (now lakes in partially drained basins), and surface seeps. To investigate how salts in uplifted marine deposits redistribute as permafrost forms under sub-aerial conditions, we conducted two main electrical resistivity tomography (ERT) surveys, one 2.3 km long and the other 1.0 km long. Both profiles began at the 2024 coastline and extended inland to higher elevations. The 2.3 km profile reached approximately 700 m beyond the Late Weichselian Marine Limit. Shallow sediment samples (0–200 cm deep) were collected to characterize near-surface porewater and sediment properties, and terrestrial laser scanning was performed along the 2.3 km transect. The ERT data suggest that salinity in permafrost is influenced by the duration and rate of uplift, as well as groundwater flow, which freshens porewater and may be partly controlled by the morphology of the intact bedrock surface. Consequently, the behavior of saline permafrost and cryopeg formation in the coarse-grained deposits of Svalbard may differ from that of finer-grained sediments in other Arctic regions, such as the Alaskan North Slope, where diffusive salt transport dominates in newly exposed marine sediments.

Textile electrodes for electrical resistivity tomography in periglacial, coarse blocky terrain: a game-changer compared to steel?

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Keywords: applied geophysics, mountain permafrost, rock glacier, landslide

Electrical resistivity tomography (ERT) is widely used to map, characterize and monitor alpine and periglacial environments with coarse, blocky surfaces. Typically, ERT measurements use steel electrodes combined with water-soaked sponges, but achieving good contact resistance between the steel electrodes and the ground to obtain high-quality data can be logistically challenging and time-consuming. To address this, we tested fist-sized, sand-filled conductive textile electrodes as an alternative to conventional steel electrodes.

We carried out ERT measurements on a landslide and two rock glaciers in the European Alps, comparing the performance of textile and steel electrodes. The precision and accuracy of the textile electrodes were tested using statistical methods, including the Wilcoxon-Mann-Whitney test, robust regression analysis and descriptive statistics.

The results showed that textile electrodes performed comparably to steel electrodes, providing good galvanic contact and accurate resistivity measurements. Measurements with textile electrodes showed lower contact resistance, which could benefit ERT monitoring. They also improved field logistics by being lighter, easier to transport and reducing the risk of injury during deployment. These advantages allow for faster ERT measurements and mapping of entire landforms.

However, textile electrodes are more susceptible to wear and tear, particularly abrasion and oxidation, and require regular replacement. Future work will explore alternative conductive materials that are cheaper and more durable. Despite this limitation, textile electrodes offer a viable, efficient alternative to conventional steel electrodes for ERT applications in difficult terrain.

Permafrost soils as a pollutant barrier – are organic contaminants released from thawing drilling mud sumps?

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Keywords: environmental pollution, organic contaminants, persistent organic pollutants (POPs), drilling mud sumps, permafrost thaw

The toxic properties and bioaccumulation capacity of numerous organic chemicals pose significant threats to environmental and human health. In the Arctic, there is evidence for accumulation processes of banned persistent organic pollutants (POPs) and further pollutants classified as chemicals of emerging Arctic concern (CEACs). Their presence in permafrost-affected soils is due to both their partitioning from the atmosphere to liquid or solid phases, promoted by the cold temperatures prevailing in the Arctic, and to direct emissions from local sources in these sparsely populated areas. The Mackenzie Delta Region, for instance, experienced extensive oil and gas exploration activities from the 1960s to the early 2000s. During this time, drill cuttings and drill fluids were disposed of in large sumps typically excavated adjacent to the well head, making use of permafrost as a natural hydrological barrier to contain the pollutants.

As the Arctic is now warming nearly four times the mean global rate, contaminant remobilization pathways to and within the Arctic are changing. Permafrost thaw may have profound effects on the inherent pollutant sink, including the 233 documented drilling mud sumps in the Mackenzie Delta region. More than half of the constructed sumps, encapsulating significant amounts of drilling fluids, now show major signs of structural failure. With sump cap subsidence and collapse, there is growing concern that organic pollutants such as oil and drilling fluid additives may be released to the environment.

In this study, we analyze soils on and downstream of four selected drilling mud sumps along the Inuvik-Tuktoyaktuk Highway. Through detailed non-target screenings of extractable organic compounds, we investigate the potential presence of various organic contaminants and assess their concentration levels above and below the permafrost table. This research aims to provide a first assessment of potential contaminant dispersion and degradation in a permafrost region impacted by the legacy of gas exploration.

Snowpack variability and its impact on permafrost at three Arctic sites (West Greenland, Siberia, Spitsbergen)

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Keywords: snow physical properties, permafrost, feedback

Permafrost in the Arctic is experiencing widespread warming and degradation, with consequences ranging from local impacts on hydrology and vegetation to global effects on carbon cycling and climate feedback. Snow cover plays a crucial role in modulating the thermal regime of permafrost, acting as an insulating layer that mitigates air temperature fluctuations during winter. Broadly, thicker snow insulates the ground more efficiently, while thinner snow may allow deeper freezing. The insulating effect of snow on soil temperatures and permafrost stability is uncertain due to variations in snow depth, density, and the formation of depth hoars. Our study investigates how the thermal properties of snow vary across spatial and temporal scales and how they influence atmospheric heat transfer to the subsurface. Our research sites span three Arctic permafrost locations with differing climate, surface, and subsurface conditions: Disko Island (West Greenland), Samoylov (Lena River Delta, Siberia), and Bayelva (West Spitsbergen). We present data from long-term observations (Bayelva, Samoylov) and project campaigns (MOMENT – Disko Island), utilizing both automated and manual snow observations.

We report on the physical characteristics of the snowpack, using a combination of automated snow water equivalent measurements, snow density profiles, and time-lapse imagery. Site-specific characteristics – such as warming and refreezing events – create internal and basal ice layers in Svalbard and Greenland, significantly altering the physical structure of the snow. In contrast, the basal snow in Siberia is characterized by thick depth hoar layers with higher insulation properties. These findings suggest potential surprises in permafrost response, driven by non-linear feedback and lag effects.

Potential of Sentinel-1 SAR remote sensing time series data for the detection of snow melt phases – comparison with in-situ ground surface temperature loggers

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Keywords: snow melt, SAR, Sentinel-1, zero curtain

Snow cover duration and timing of snowmelt are important factors in periglacial environments: The snowpack affects heat flux between the subsurface and atmosphere due to its insulating properties and acts as water storage and supply influencing liquid water availability. As snow cover duration usually shows high spatial heterogeneity, in situ observations have limited capabilities to monitor variations on larger scales with high spatial coverage. Well-established optical remote sensing approaches experience challenges due to frequent cloud coverage and, at high latitudes, polar night. Further, optical sensors are insensitive to the liquid water content and, therefore, cannot differentiate between wet and dry snow. However, several studies have shown that SAR remote sensing is capable of detecting wet snow but comparative analyses with in-situ observations so far remain limited.

Therefore, we compare Sentinel-1 derived snow melt phases (runoff onset and melt-out) with the start and the end of the zero curtain phase observed in the temperature logger time series. Results show that the start of the zero curtain phase (runoff onset) can be detected with an RMSE of 12 days and the end of the zero curtain phase (melt-out) with an RMSE of 20 days. The decreased accuracy for the latter can be explained with the effects of microtopography and different spatial resolutions of the satellite data (20 m pixel size) and in-situ measurements as especially loggers located on elevated terrain often detect the end of the zero curtain phase around 40–60 days earlier than the SAR-derived melt-out date. This preliminary analysis indicates the high potential of SAR time series data for the detection of snow melt phases.

More information about snowpack properties could further increase the understanding, how the SAR signal reacts to changes in the snowpack and how SAR could be used to monitor snowmelt phases at larger scale.

Predisposing, triggering and runout conditions of two rock slope failures in the French Alps: Vallon d'Étache and Crête des Grangettes

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Keywords: rockwalls monitoring, permafrost modeling, electrical resistivity tomography, rock slope failure propagation modeling

In high mountain environments, permafrost degradation causes rockwall instabilities, sometimes leading to rock slope failures threatening human lives and activities. It is therefore essential to improve our knowledge about their triggering and propagation mechanisms.

This study focuses on two rock slope failures which occurred in the Vallon d'Étache (Maurienne Valley, France) and the Crête des Grangettes (Écrins massif, France) in 2020. These events have volumes around 225'000 m^3 and 35'800 m^3 respectively. In both cases, ice in the scars suggests the presence of permafrost, but its local distribution and its role in the triggering of the events remain to be confirmed. The aims of this study are (i) to assess thermal conditions in which both events were triggered and (ii) to understand the propagation mechanisms in the Vallon d'Étache. To do so, we combine rockwalls temperature monitoring, permafrost statistical modeling, geophysical surveys (Electrical Resistivity Tomography) and laboratory measurements (petrophysical model) to explain the thermal conditions predisposing and triggering the events. Depth-averaged flow simulations are used to model the runout characteristics of the Vallon d'Étache rock avalanche.

This multi-method approach shows that both of the events occurred in bedrock with permafrost subject to intense warming since the 1990's with a sharp acceleration in the ground temperature rise since 2015. In the Vallon d'Étache, thermal analysis suggests that the rock avalanche may have been triggered by permafrost warming (from cold to warm permafrost) combined with heavy rainfall and water infiltration. This likely interacted with ice within rock fractures, increasing hydrostatic pressure and/or accelerating ice degradation within the fractures. At the Crête des Grangettes, the warming of temperate permafrost, nearing its melting point, likely reduced the strength of the ice within the fractures, triggering the rockfalls.

Spring hydrochemistry of three active rock glaciers and its relationship with their morphodynamics

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Keywords: climate change, rock glacier, ground ice, water resource

Rock glaciers play a significant role in high mountain watersheds by temporarily storing liquid and solid water. Since the melting of ground ice could represent a valuable long-term water resource under the influence of climate change, it is essential to understand its impacts on rock glacier springs better. However, quantifying ground ice content and related processes (thawing, melting, refreezing) is challenging. Hydrogeochemical analysis of rock glacier springs can help gain more insight. This study examined the spring hydrochemistry and the influence of morphodynamical processes of three active rock glaciers (Monte Prosa A, Ganoni di Schenadüi and Piancabella) in the Swiss Alps.

During the warm season, water samples were collected from rock glacier springs, precipitation, snowpack and seasonal ground ice. Isotopic analysis ($\delta^{18}O$) showed a seasonal increase in $\delta^{18}O$ in rock glacier springs, reflecting a shift from snowmelt-fed supply to more ^{18}O-enriched water. Ion chromatography analysis revealed a seasonal increase in ions (e.g. SO_4^{2-}, Ca^{2+} and Na^{+}) in rock glacier springs.

To monitor seasonal changes in rock glacier morphodynamics, repeated Unmanned Aerial Vehicle and differential Global Navigation Satellite System surveys were conducted. The comparison between dense point clouds obtained through Structure from Motion photogrammetry showed significant changes in elevation. In particular, over the 2023 warm season, subsidence was observed in the rooting zone of two rock glaciers (Monte Prosa A and Ganoni di Schenadüi), with thickness losses ranging from about 0.2 to 0.6 m.

These findings suggest that ground ice melting affects both spring hydrochemistry and morphodynamics of the investigated rock glaciers. A relationship was observed between seasonal increases in water chemistry values, indicating an increasing inflow of meltwater from ground ice, and increased deformation (particularly, subsidence that occurred locally at Monte Prosa A and Ganoni di Schenadüi rock glaciers), which could be indicative of increased thawing and melting of ice.

Influence of land surface temperature on permafrost dynamics – a Northern Hemisphere perspective

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Keywords: remote sensing, AVHRR, MODIS, modeling

Permafrost cannot be directly observed from space. However, land surface temperature (LST), snow, and land cover information derived from satellite observations can be used as input variables for permafrost models. LST can be used as an indicator of the thermal state of the ground and has, in the last decade, been increasingly used in arctic research and permafrost modeling. Currently, LST datasets based on Moderate Resolution Imaging Spectroradiometer (MODIS) are the most frequently used thanks to their medium spatial resolution (~1km) and extended data coverage (more than 20 years). For example, MODIS LST and ERA5 reanalysis data have been used in the past to force CryoGrid 1, an equilibrium model, designed to compute the mean annual ground temperature at the top of the permafrost table. Using this model, high-resolution (1 km) permafrost maps of the Northern Hemisphere were produced (Obu et al., 2019). A drawback is that MODIS LST products have only been available since 2001, which prevents differentiating multi-decadal climate trends from decadal-scale climate oscillations.

To address this limitation, a new Pan-Arctic LST dataset based on EUMETSAT's Advanced Very High-Resolution Radiometer (AVHRR) Fundamental Data Record (FDR) published in May 2023 has been developed. The new Pan-Arctic AVHRR LST product covers a period from 1981 to 2021 and has a spatial resolution of approximately 4 km. The newly developed Pan-Arctic AVHRR LST dataset is integrated into the CryoGrid model, enabling a comprehensive comparison between modeling outcomes based on AVHRR LST and MODIS LST across various regions of the Pan-Arctic. Additionally, the AVHRR dataset facilitates a detailed investigation into permafrost dynamics over the past four decades, providing valuable insights into long-term permafrost extent and changes in selected Arctic areas.

Deciphering the evolution of rockglacier Murtèl by a multi-methodological approach

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Keywords: mountain permafrost, rockglacier, dating, modeling

Rockglaciers are distinct morphological indicators for the current and former occurrence of permafrost and act as important debris-transport systems in periglacial environments. For the enhanced use of these landforms as palaeoclimatic indicators, more insights are needed towards landform dynamics, genesis and evolution.

In the European Alps, several attempts have been made in recent years to compile and reconstruct rockglacier ages; by description of flow-lines of horizontal surface velocities (Kääb et al. 1998), by surface-exposure dating (Haeberli et al. 2003, Amschwand et al. 2021), by ^{14}C dating of organic material from ice cores (Krainer et al. 2015), and modeling approaches (e.g. Müller et al. 2016).

In a recent attempt, we follow a multi-method approach to decipher the evolution of rockglacier Murtèl in more detail (surface and depth). The corresponding data result from:

- Monitoring of subsurface deformation
- Geodetic surveys
- Analysis of aerial images
- ^{14}C dating of water-insoluble organic carbon
- Numerical age-layer modeling

Our multi-method approach provides insight into the recent dynamics as well as the long-term evolution of rockglacier Murtèl. The combination of recent annual as well as decadal velocities indicates a possible range and temporal variability of creep rates over centuries and millennia. Nevertheless, distributed surface ages derived from surface velocities fit relatively well with the subsurface ages at a single location. Despite the fact that more datings are needed (and expected) from additional depths, the existing ages allow to determine the dominant processes for the genesis and long-term rockglacier evolution after deglaciation on this slope.

Regional application of standardized guidelines for rock glacier inventory in the Swiss Alps

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Keywords: geomorphology, permafrost, rock glacier, geomorphological mapping, GIS, remote-sensing, RGIK

Rock glaciers are debris landforms typical of high mountain environments. They can be identified in the landscape by their steep frontal and lateral margins, as well as their lobed surface and the frequent occurrence of ridges and furrows (RGIK, 2023). Their morphology is related to the downslope creeping movement. Over the recent years, the scientific community has highlighted the importance of studying these landforms to improve our understanding of the impacts of climate change on high mountain regions and specifically on alpine permafrost.

The RoDynAlps research project, funded by the Swiss National Foundation and led by the Universities of Fribourg, Lausanne, Zurich and the WSL Institute for Snow and Avalanche Research, aims to better understand the dynamics of rock glaciers in the Swiss Alps. One of the main objectives of the project is to assess the current state of the rock glaciers in the Swiss Alps, by compiling a comprehensive inventory of rock glaciers in the Swiss Alps, including kinematic characterization.

To this aim, standard guidelines developed by a consortium of experts (RGIK, 2023) are currently applied to the whole Switzerland. We present the results obtained in the Bagnes-Hérémence area, in the Valaisan Alps. We found more than 300 rock glaciers between 2000 m and 3200 m asl, covering more than 750 hectares and representing approximately 3.5% of the non-glaciated area (in 2016) above 2000 m. 140 landforms are active, with average deformation rates ranging from several decimeters to one meter per year. Additionally, seven rock glaciers are destabilized, exhibiting abnormal annual displacements of up to 5 meters.

Saline permafrost controlling retrogressive thaw slumps

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Keywords: arctic, retrogressive thaw slump, ert, geophysics, saline permafrost

Saline permafrost occupies a significant portion of the northern hemisphere along shorelines and coastal permafrost areas. The salt content in this permafrost can lead to freezing point depressions, meaning unfrozen hypersaline material exists at sub-zero temperatures. This can lead to unexpected geomorphological changes, when permafrost temperatures rise above the freezing point, a factor that usually is not implemented in models predicting permafrost thaw.

A rising number of retrogressive thaw slumps (RTS) in Arctic permafrost increases the risk for long-term infrastructure stability. As the behavior of RTS is hardly predictable, a detailed investigation of the geological setting and the controlling ice availability are often required to make assumptions about their future behavior. How a variable salt content and a freezing-point depression influence the behavior of RTS has not previously been studied. We use a combination of stratigraphic logging, different laboratory analyses and Electrical Resistivity Tomography (ERT) to investigate how saline permafrost impacts RTS development and behavior.

The goal of the study is to better predict the future behavior of retrogressive thaw slumps and establish a bundle of techniques necessary to understand the geomorphological impact of saline permafrost.

Rock glacier velocity in Rio Molina Catchment, semiarid Andes of Chile

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Keywords: rock glacier, mountain permafrost, Andes

Cryospheric components in the semiarid Andes of Chile are crucial freshwater sources for both ecosystems and communities. While the changes in glaciers in this region have been extensively documented – showing continuous recession and downwasting – studies and systematic measurements of viscous creep features, such as rock glaciers, which carry ice-supersaturated debris in perennially frozen ground (permafrost), remain limited.

The objective of this study is to quantify and characterize the velocity of rock glaciers (RGV) on 50 morphologically active landforms situated within the Molina River catchment area. This aims to provide enhanced insights into the ongoing changes in mountain permafrost. To achieve this, we employed near-annual very high-resolution images from the Pléiades satellite constellation, captured between 2013 and 2024, obtained from both archive and acquisition modes. Furthermore, the most recent guidelines from the Rock Glacier Inventories and Kinematics (RGIK) initiative were applied, encompassing both geomorphological and kinematic inventory approaches. As changes in RGV can serve as a proxy indicator of the current state of mountain permafrost, extensive measurements were conducted using image co-registration, multi-temporal block adjustments, and feature tracking across the entire dataset.

Preliminary results indicate that the RGV velocities for most of the landforms range between 0.10 and 0.85 m/yr, which is considerably slower than rates observed in other mountain regions. Despite the complex and poorly constrained ground thermal conditions, it has not been possible to establish a clear trend (acceleration versus deceleration) for the study landforms. This study focuses on one of the largest permafrost regions in the Southern Hemisphere and one of the most rock glacier-abundant areas worldwide.

Permafrost temperatures near an Arctic landfill, Longyearbyen, Svalbard

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Keywords: Arctic permafrost, waste management, ground temperatures, climate impact

Waste disposal in the Arctic involves numerous challenges due to the region's harsh, remote environment, permafrost conditions, climate change, and the fragility of the Arctic ecosystem. In 2017, 66.1% of Arctic communities were situated on permafrost. Waste from these communities is still primarily disposed of in landfills. To ensure environmentally safe and sustainable waste management, and ultimately achieve the permanent closure of Arctic landfills, it is essential to carefully evaluate factors such as the thermal state of the ground and the effects of climate change.

We examine a solid waste landfill situated in the Advent Valley on Svalbard, approximately nine kilometers southeast of Longyearbyen. The landfill is placed directly on the ground, with no constructed sealing layer separating the original soil from the waste and is entirely located below the marine limit. We analyze five years of ground temperature data, down to depths of 11–12 meters, both around and within the landfill, in relation to recent temperature trends in a deep borehole in Longyearbyen, which was established in 1985.

Borehole temperatures in all five boreholes outside the landfill suggest a zero annual amplitude slightly below 11 m and mean annual ground temperatures in the range of –1 to –2.5°C, with maximum active layer depths at undisturbed locations reaching down to 1 to 2 m. This is in the same range as reported for other sites near Longyearbyen, but warmer than the mean annual ground temperature (at 10 meters depth) of –2.8°C, measured in the deep borehole at the beach (Gisnås et al., 2023). Near the landfill, our results point to permafrost degradation due to water accumulation at a concrete wall intended to mitigate effects of water flow. Borehole temperature measurements at the landfill reveal, furthermore, that there are no permafrost conditions below the landfill today.

Deciphering controls of cryogenic lahars at Chimborazo volcano, Ecuador

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Keywords: debris flow, glacier retreat, permafrost, trigger mechanism, geophysical investigation

The unprecedented occurrence of cryogenic, secondary lahars in the last decade posed a major threat at glacierised volcanoes in Ecuador. The lahars originate close to the glacier margins of rapidly retreating tropical glaciers with unknown trigger mechanisms. Ecuadorian glaciers have experienced a rapid decline of up to 50% of surface area within the last 40 years, and future rise of the ELA with up to 200 m within the next 50 years.

In this study, we develop a conceptual model and employ meteorological, geophysical and geomorphological reconnaissance and IR UAV-surveys at Chimborazo (EC, 4700–4900 m asl) to decipher starting conditions of secondary cryogenic lahars, a scientifically nearly undescribed phenomenon. Along the covered ice body extending below Glacier Nicolas Martínez, we investigate known starting zone of at least 5 secondary cryogenic lahars with 2 ERT cross-sections (approx. 200 & 300 m long) to decipher ice contents, 6 temperature loggers along transects and at known debris-covered ice sites to calibrate IR surveys flown with a Mavic 2 EA drone. Optical data and geomorphological field reconnaissance found exposed ice in former debris-covered glaciers but also in former side moraines which are now ice-cored, underlining the transition into a permafrost-dominated setting. By a systematical comparison with our conceptual model we can show that only few genetic types comprise a majority of relevant starting conditions for cryogenic secondary lahars. Here we show, how cryogenic secondary lahars evolve in degrading debris-covered glaciers subsequent to rapid glacier retreat along tropical volcanoes, a problem whose importance is rapidly growing in the foreseeable future.

ILLUQ — Permafrost, pollution, health: field activities along the Yukon Coast in 2024

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Keywords: permafrost, Arctic, mercury, Beaufort Sea, coastal erosion

Permafrost thaw releases large quantities of contaminants into the environment. In fact, permafrost soils store nearly twice as much mercury as all other soils, the ocean, and the atmosphere combined. This mercury is vulnerable to release as permafrost thaws and coastlines collapse today and in the future. Contaminants, including heavy metals, persistent organic pollutants and microbiological agents locked in permafrost, are a risk for both human and animal health. Yet the social, physical and health components of permafrost thaw have traditionally been studied in isolation, leading to inadequate policy options that ignore the holistic nature of the threat. There is a need for an integrated and participatory approach to the complex issues at the overlap between climate change, permafrost thaw, infrastructure damage, contaminants, health and well-being and for solutions founded on the cultural, natural and social frameworks of local communities.

ILLUQ is an interdisciplinary EU-project rooted in participatory research with local stake- and rightsholders. Its mission is to provide a holistic approach to permafrost thaw, pollution, One Health and well-being in the Arctic and delivering timely products on the threats from contaminant release, infrastructure failure and ecosystem changes to stakeholders. ILLUQ's endeavor is a direct answer to the pressing needs of communities located on permafrost. It targets the missing link between studies performed by scientists, engineers and consultants in local communities and solutions with local stake- and rightsholders. ILLUQ focuses on three main areas in the Arctic: Svalbard, West Greenland and the Mackenzie Delta area.

In this presentation, we introduce the project and its activities during the 2024 summer expedition along the Yukon Coast. We aim to develop a comprehensive framework for stocks and fluxes of mercury along the Yukon mainland coast and its fate in the nearshore zone of the Canadian Beaufort Sea.

Quantification of heatwaves and their impact on the alpine permafrost

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Keywords: permafrost, heatwaves, geophysical monitoring, Alps

The causes behind alpine permafrost thawing are multifactorial, with most abrupt active layer thickening observed after hot summers. As intensity of heatwaves increases, it becomes crucial to quantify their impact to identify a potential tipping point beyond which permafrost may not recover. Although existing climatological studies provide several tools for analyzing heatwaves (Perkins & Alexander, 2013), these have not been widely applied to Alpine settings. Here we employ the Heat Wave Magnitude Index daily (HWMId) metric (Russo et al., 2015) for temperature analysis from PERMOS and MeteoSwiss stations near prominent Swiss permafrost monitoring sites. Historical and reconstructed data determine site-specific temperature thresholds, as systematic heatwave definitions do not apply uniformly. Beyond observations in borehole temperatures, using the petrophysical joint inversion (Wagner et al. 2019), the HWMId can be compared to time series of ground ice content time series obtained from geophysical data inversions (seismic refraction and electrical resistivity tomographies). Case studies at Schilthorn and Stockhorn highlight the role of the sediment cover and morphology of the site. Analysis of multidecadal temperature and geophysics data shows accordance between decreasing ground resistivity and increasing heatwave frequency and intensity. Further analysis would benefit from integrating metrics like freezing/thawing degree days and considering local geomorphology. Expanding the study to additional PERMOS sites could provide insights into permafrost resilience across landforms.

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The 2023 Fluchthorn rockfall: before and after the event

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Keywords: rockfall, permafrost, debris-flow, thermokarst, hydrology

On 11 June 2023, a massive rock avalanche occurred in the Silvretta mountain range near Galtür, Austria, originating from the Southern Fluchthorn summit and releasing approximately 950'000 m^3 of rock debris into a snow- and (partially) ice-covered deposition zone. This event resulted in a 19-meter reduction in summit elevation (from 3399 to 3380 m) and a debris flow which flooded the lower Futschöl valley. By integrating historical data, high-resolution airborne laser scans, as well as glaciological, meteorological and hydrological records, we analyze the natural events leading up to the rockfall and its evolution into a debris flow.

Temperature data from nearby weather stations did not reveal significant warming in the weeks before the event. However, strong snowmelt rates and intense rainfall before may have contributed to trigger the event. Additionally, hydrological measurements along the Jamtal river show a peak flow rate consistent in time with the rock avalanche indicating the release of water during the event followed by a runoff reduction due to damming effects in the deposition area. The rock debris first hit the area of a debris-covered glacier, the Fluchthornferner. This same area was covered under ca. 1.4 m snow at the time of the impact. The Fluchthornferner has experienced a significant retreat since 1850, losing 60% of its area. It disintegrated into several parts and the southern tributary completely vanished in 2018. The ice loss on the main glacier has steepened the glacier's surface slope, as demonstrated by digital elevation models (DEMs) and LiDAR data spanning from 1969 to 2018. Notably, a meltwater thermokarst lake at 2'686 meters contributed to the destabilization prior to the avalanche. The water of the thermokarst lake, together with the snow and ice melted by the energy of the impact contributed to the transition into a debris flow.

Assessing permafrost conditions in the detachment zones of three large cold-mountain slope failures in 2023

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Keywords: permafrost, rock/ice avalanches, recent events, cold mountains

As a contribution to a focused international-interdisciplinary learning process, permafrost conditions were assessed for the detachment zones of three large recent events. At Rasac arête (Cordillera Huayhuash, Peru), about 1.1 to 1.5 million m^3 detached in February 2023 from cold/deep permafrost near 5800 m asl with mean annual surface temperatures estimated at –5 to –6°C and thermally protected by intact ice aprons. The resulting rock/ice avalanche impacted Lake Rasac but without damage to inhabited areas. The detachment after precursory mobility signs at 3800–3900 m asl of 1 million m^3 of perennially frozen rocks at Glacier Tbilisa (Caucasus, Georgia) on 3 August 2023 caused severe damage and losses of lives at Shovi; it took place at a site where mean annual surface temperatures are estimated at –2 to –4°C. About 15 million m^3 from the large perennially frozen left lateral moraine (5300 m asl) slid into the deep and rapidly growing proglacial South Lhonak Lake (Sikkim Himalaya, India) on 3 October 2023, causing a devastating long-distance down-valley flood with heavy damage and losses of lives in a transboundary situation including Bangladesh. With mean annual surface temperatures of about –1 to –3°C and a maximum slide depth of 88 m, the rupture may well have taken place in warm permafrost or even at its base. In accordance with information from research on viscous creep in mountain permafrost (rock-glaciers), ice content of the failed moraine is estimated at some 60–80%. This excess ice content or ice-supersaturation enabled rapid large-scale creep movements with a strikingly coherent flow field and annual displacement rates up to 15 m in the years before the event. Movements are ongoing, and massive bodies of buried ice have been exposed within the outlet channel of the lake deeply eroded in creeping ice-rich perennially frozen morainic material.

Tipping points and resilience of mountain permafrost under increasing frequency of heat waves – the TREAT project

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Keywords: mountain permafrost, tipping points, heat waves, geophysics, modeling

Mountain permafrost is currently undergoing major changes showing clearly detectable ground temperature increase and ground ice content loss. On regional scales, it becomes standard to quantify ground ice loss through electrical, seismic and electromagnetic techniques. Recently developed joint inversion approaches combining different tomographic techniques allow for ground ice loss quantification over time (Steiner et al. 2021, Morard et al. 2024).

The recently funded TREAT project addresses current research questions regarding the future evolution of mountain permafrost such as the existence of tipping points causing irreversible permafrost degradation, the influence of anomalously hot periods (Hauck & Hilbich 2024), the resilience of coarse-blocky substrates to warming events and whether thawing permafrost slopes become wetter or drier in future. Consequently, we further develop geophysical joint inversion techniques and numerically couple a thermo-hydraulic permafrost model to geophysical monitoring data from several observatories in the Alps (Maierhofer et al. 2024). First results of the project and potential paths for future research will be presented.

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New permafrost boreholes and geophysical observations in Central Asia

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Keywords: climate change, permafrost, borehole temperatures, geophysical observation

Climate change poses a significant challenge to humanity, with its global repercussions threatening economies and livelihoods for future generations. Developing effective strategies to enhance climate resilience through adaptation requires reliable baseline data, including climate observations and the Essential Climate Variables (ECVs) identified by the Global Climate Observing System (GCOS). However, substantial gaps persist in the global climate observing system, especially in high-altitude mountain regions. This issue is particularly pronounced in developing countries, where baseline data is either lacking or at risk of being continued, therefore also increasing uncertainty about the impacts of climate change. Such information is crucial for predicting future changes and devising appropriate adaptation strategies.

Climate change in the mountainous regions of Central Asia significantly affects water resources and increases the frequency and intensity of natural hazards. To address these challenges, the *Cryospheric Observation and Modelling for Improved Adaptation in Central Asia* (CROMO-ADAPT) project has focused on closing data gaps and strengthening cryospheric monitoring systems, including snow, glaciers, and permafrost. As part of this initiative, new permafrost boreholes have been installed across Central Asia.

Three boreholes, each approximately 30 meters deep, were drilled at sites in Kazakhstan (Zholsalykezen Pass), Kyrgyzstan (Akshiirak), and Tajikistan (Uy Bulak Pass). All boreholes confirmed permafrost conditions and are continuously monitored. Recorded temperatures at 20 m depth are approximately –0.17°C in Kazakhstan, –1.6°C in Kyrgyzstan, and –1.1°C in Tajikistan. Additionally, geophysical surveys have been conducted at these locations and are compared with the borehole data to provide a more comprehensive understanding of permafrost conditions.

"Fjellviten": advancing real-time permafrost monitoring and public engagement in Norway's high mountain regions

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Keywords: mountain permafrost, real-time monitoring, public involvement

The "Fjellviten" (Mountain Knowledge) project, initiated by the Norwegian Mountain Center in partnership with national research institutions, seeks to actively engage the Norwegian public, especially young people, in the monitoring of mountain permafrost. The project focuses on enhancing real-time permafrost and climate monitoring in the high-altitude regions of Norway, particularly in Jotunheimen, and aims to foster greater public involvement in understanding climate change impacts in these areas.

Over four years, it will establish digital and physical platforms for data sharing, with a strong emphasis on involving high school students in developing knowledge and get a broader understanding of how climate research is carried out. These efforts will benefit students across Norway, particularly those near Jotunheimen, while also broadening public access to permafrost and climate data on both national and international levels through modern communication tools.

The project area in Jotunheimen is a high-altitude plateau situated at approximately 1800 m asl, surrounded by Norway's highest peaks, which reach up to 2500 m asl. Jotunheimen has been the focus of extensive permafrost research over the past 50 years and is home to the deep borehole (129 meters) at Juvvasshøe established by the PACE (Permafrost and Climate in Europe) project in 1999.

As part of the project, new boreholes were drilled to a depth of 45 m adjacent to the University of Oslo's 10 m deep boreholes Juv-BH1 on Juvflye (1851 m asl) and Juv-BH3 at Dugurdskampen (1546 m asl) with continuous data dating back to 2008 and selected observations dating back to 1982.

The boreholes are upgraded with new thermistor cables and data loggers for real-time data transmission, integrating them into the operational permafrost monitoring program at the Norwegian Meteorological Institute to ensure long-term operation. Daily updates and data visualization products will be available on https://cryo.met.no/permafrost, supporting the digitalization strategy in the project.

Quantifying mercury (Hg) release from coastal erosion along the Yukon Coast, Canada

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Keywords: mercury, coastal erosion, Yukon coast, permafrost coasts

Permafrost stores large amounts of mercury (Hg), locking this toxic element in frozen soils across the Arctic. Mercury and its organic form methylmercury, in particular, is a neurotoxin which accumulates along the food chain. With increasing rates of coastal erosion driven by rising air and ground temperatures, Hg is being mobilized and released into the Arctic Ocean. This process does not only threaten local ecosystems but has broader implications, as Hg might be transported over long distances or taken up by marine organisms, posing risks to both wildlife and human health. To better understand such risks, we aim to quantify the amount of Hg that is stored in permafrost and released by coastal erosion along the Yukon Coast, Canada. Samples were taken from various landscape features including permafrost cliffs, active layer, and marine sediments along the Yukon Coast and on Herschel Island-Qikiqtaruk. We analyzed over 70 samples for elemental mercury, organic carbon, nitrogen, and grain-size distribution, and supplemented these results with existing data from previous field campaigns and the literature to create a regional database. Based on these data we will first estimate Hg stocks in the upper permafrost for the Yukon Coast. Combined with coastal erosion rates we will then estimate annual Hg fluxes into the ocean for this region. Together with Hg concentrations in marine sediments our findings will provide a clearer picture of the Hg stocks, fluxes, and its fate along the Yukon Coast. These data are crucial for decision makers and might help to assess Hg exposure to Arctic wildlife and human populations, whose diet largely relies on marine biological resources.

Greenhouse gas production during the transition from terrestrial to marine permafrost environments

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Keywords: coastal landscape change, microbial response, thermokarst lagoons, carbon cycle, CO_2

More than 30% of the world's coastlines are affected by permafrost, which is often rich in organic matter and ground ice and highly sensitive to climate change. Along these ice-rich coasts, rapid sea ice loss, rising temperatures, and stronger storms accelerate erosion. In expansive coastal lowlands, retreating coastlines transform thaw lakes and drained lake basins into thermokarst lagoons, forming through two main pathways: either as freshwater lakes that transition directly to brackish or saltwater lagoons, or through freshwater lakes that first drain, allowing permafrost to redevelop before subsequent seawater inundation.

As thawing progresses, organic carbon is exposed to microbial decomposition, releasing greenhouse gases (GHGs) like carbon dioxide (CO_2) and methane (CH_4), further contributing to climate warming. However, the role of thermokarst lagoons in the permafrost carbon cycle remains unclear. To investigate, we conducted long-term anoxic incubation experiments on surface samples from thermokarst lagoons, terrestrial permafrost, the active layer, and lake sediments. We focused on lagoon systems across the coastal lowlands of NE Siberia, N Alaska, and NW Canada, analyzing CO_2 and CH_4 production along land-sea transitions. Additionally, we mapped thermokarst lagoons along Arctic coastlines using remote sensing.

Our findings indicate that GHG production is significantly higher in lagoon sediments than in terrestrial permafrost, active layers, or lake sediments. While there are regional differences, the variation in GHG production across landscape types is more substantial. By combining incubation results with spatial mapping, we estimated that thermokarst lagoons could release an average of 3 Tg CO_2-equivalent annually by 2100. Although small in area (3'457 km^2), thermokarst lagoons release over four times the CO_2-equivalent per unit area compared to thermokarst lakes, marking them as significant carbon release hotspots. As climate scenarios project accelerated coastal erosion and rising sea levels, thermokarst lagoons may play an increasingly important role in Arctic carbon budgets.

Spitze Stei: 16 Mio. cubic meters of rock are threatening one of the Alps' most frequented tourist hot spots

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Keywords: rock slope failure, Spitze Stei, hydology, permafrost

Spitze Stei is one of the largest, failure-prone rock slope instabilities in the European Alps. Over the last 5 years, annual displacement rates of more than one meter have been recorded. The slope is located above Kandersteg in the Bernese Alps, Switzerland, in a region affected by several extremely large prehistoric rockfalls. The tourist site Öschinensee below the slope was formed by one of these. The current destabilization was accompanied by thawing of large parts of the slope. Detailed investigations of slope kinematics, displacement velocities, ground temperatures, geohydrology and geotechnical properties of the rock mass indicate that permafrost may have been the decisive trigger for the reactivation of slope displacements in this area. After the initial destabilization phase, the slope displacement rates are currently in a labile balance, characterized by a distinct seasonal signal but no clear long-term trend. Hydrological models and tracer tests indicate that the slope contains a large water reservoir. Moreover, the level of this reservoir turned out to be an almost perfect indicator of seasonal velocity changes and thus for the early recognition of critical acceleration events. The transition to such a critical phase could lead to catastrophic failure events. Although potential rock avalanches will not reach settlements, extensive debris flow activity is expected, causing a redeposition of rock mass into the settlement area of Kandersteg.

Elevation-dependent warming in the Central Himalayas, India, from the perspective of high mountain hazards

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Keywords: elevation-dependent warming (EDW), glacial lake outburst floods (GLOFs), climate change

Elevation-Dependent Warming (EDW) in the Indian Himalayas, characterized by accelerated warming at higher altitudes, is increasingly impacting permafrost stability, rock glaciers, and glacier-fed lakes. This study explores the connections between EDW, glacial lake expansion, and the destabilization slopes at high altitudes. The satellite remote sensing-based data has been used to analyze the pattern of surface temperature variability in the central Himalaya at higher altitudes to understand the EDW patterns and their numerous effects as causative factors on high mountain hazards such as glacial lake outburst floods (GLOFs) and snow/ice/rock avalanches. The majority of the hanging glaciers are located at the steep slopes above 5000 m asl in this part of Himalaya which are tremendously vulnerable to the temperature variability. The slope instability in high-mountain regions has very well been linked to increase in temperature and the associated permafrost degradation and/or the increase in frequency/intensity of rainstorm events. Our temperature analysis showed significant variability and a rising trend in recent years during winter and as well annually at elevations above ~4000 m asl. The recent events in the Chamoli region, Kedarnath region, Manasalu region and Dokriani region very clearly presented the evidence of impacts of temperature variability at higher reaches. Further, it has been observed that the glacial lakes are increasing in number and expanding faster at higher altitudes as compared to lower altitudes.

First year of automated electrical resistivity tomography (A-ERT) measurement on James Ross Island, Antarctica

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Keywords: electrical resistivity tomography, permafrost monitoring, active layer, ground thermal regime, Antarctica

This study aims to investigate the connection between different physical parameters of the ground in permafrost environments, namely electrical resistivity, temperature and water content. The area of interest is located on James Ross Island in the north-eastern part of the Antarctic Peninsula. It is underlain by continuous permafrost and experiences semi-arid polar continental climate with a mean annual air temperature around –7°C. An automated electrical resistivity tomography (A-ERT) setup using a 4POINTLIGHT_10W (Lippmann) device was installed in the vicinity of the Czech Antarctic station Johann Gregor Mendel in late February 2023. The setup measures ground electrical resistivity daily across a 23-meter transect using 47 electrodes with 0.5 m spacing. The transect consists of two distinct lithologies – a Holocene marine terrace and finer-grained Cretaceous sediments. The lower boundary of the A-ERT investigation depth lies approximately 4.5 meters below ground surface in the middle of the profile. Several temperature (sensors placed at 5, 10, 20, 30, 50, 75, 100, 150 and 200 cm) and soil moisture (sensors at 5, 35, 55 and 75 cm depth) profiles are installed at different points along the transect. With data spanning now approximately one year, we demonstrate how different lithologies affect ground thermal and moisture regime and subsequently its resistivity to electrical current flow. Typically, resistivity values are much higher in the winter (ca. 1–2 kΩm) and decrease abruptly as the ground thaws (ca. 10–100 Ωm). Ground temperature and soil moisture both exert direct control over the resistivity changes. During the thawing phase, the progression of the thaw front is clearly visible from the resistivity data. So far, A-ERT has proven a rugged and reliable way to monitor the state of permafrost in the harsh conditions of Antarctica over larger profile distances, providing data beyond the capabilities of the traditional borehole measurement approach.

Does the 2023 Fluchthorn massive permafrost rock slope failure answer longstanding questions in permafrost and landslide research?

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Keywords: permafrost, rock slope failure, hazards, mechanical model

Here we combine the latest complementary expert knowledge to decipher the 1 Mio. m^3 Fluchthorn rock slope failure that detached on 12 June 2023, from the before 3399 m high summit causing a rock avalanche that additionally eroded ca. 120.000 m^3 of ice. InSAR data shows deformation rates from April 2021 to March 2023, linked to a westward deformation of the entire Silvretta nappe over-steepening the Fluchthorn. Mountain guides observed singular failures before the event. IR drone flights immediately after the event indicate rock temperatures at the failure planes in the range of 0°C to –2°C and ice-filled fractures. Solid, scarcely fractured pseudotachilitic sequences in the summit regions may have contributed to the massive over-steepening of the Fluchthorn Westface without significant pre-failures. The grain size compositions shows massive material take up of fine-grained material and fragmentation.

In a seismic analysis we can for the first time exactly reconstruct the temporal and spatial trajectory of a rock-ice avalanche, velocities and energy release during the 120-second rock-ice-avalanche propagation consistent with fragmentation and deposits. High-resolution photogrammetry highlights massive ice erosion and accumulation patterns during the rock avalanche propagation. In addition, we analyze all precursors in the last two years before the failure in detail. These include small pre-failure volumes, seismic precursors, kinematic precursors and kinematic precursors detected in UltraCam & LiDAR surveys.

In an IRAZU model, capable of nucleation and growth of fractures based on nonlinear fracture mechanics applied stresses act to produce a progressive fracturing path that closely resembles the real failure and we can show the impact of the solid pseudotachilitic roof on the oversteepening. In a discontinuum model (UDEC), we can show the stabilizing effect of permafrost on developing fracturing patterns in a combined rock-ice mechanical approach including temperature-dependent rock mechanical and destabilization processes in ice-filled fractures and along rock-ice interfaces.

The influence of glacier-permafrost-interactions on recent morphodynamics in alpine glacier forefields

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Keywords: glacier-permafrost-interactions, geophysics, DInSAR

In the European Alps, thrust moraine complexes are relatively rare due to the comparatively extensive glacial advances during the Little Ice Age (LIA), usually below the local lower permafrost boundary. Due to the complex formation, which may also be partly attributable to multiple glacial advances, permafrost-related ground ice, but also large amounts of sedimentary ice of glacial origin are often incorporated into these moraine complexes. The high amounts of ice within their internal structures make them especially sensitive to external changes, particularly climate warming. High ice contents also enable permafrost creep and internal deformation of the moraine complexes resulting in distinct morphodynamics. General spatial patterns and their temporal variations, but also their relationships to subsurface structures are key components to understand their origin and the future development of these landforms.

In the current research project, we investigate the internal structures of several thrust moraine complexes in the Swiss Alps using geophysical methods. The use of electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) enables the detection of massive ice bodies and differentiation between ice of glacial and periglacial origin (sedimentary and magmatic ice) in the subsurface of such landforms. Additionally, Differential SAR Interferometry (DInSAR) based on Sentinel-1 data provides information about recent morphodynamics. A comparison of the geophysical and remote-sensing data should help to understand the linkages between the subsurface structures and the surface dynamics of these landforms. Besides, the coexistence of thrust moraines and active rock glaciers at the study sites enables the comparison of morphodynamic similarities or differences between both landform types.

Out of the freezer: quantifying organic matter reactivity and decomposition rates in thawing Arctic subsea permafrost

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Keywords: subsea permafrost, incubations, modeling, microbes, carbon

Subsea permafrost (SSPF) is expected to thaw at accelerating rates in the coming centuries as bottom water temperatures increase in the Arctic Ocean. Organic matter (OM) preserved in SSPF will become increasingly available to previously dormant microbes, leading to increased decomposition rates and, thus, production of methane (CH_4), carbon dioxide (CO_2), and the recycling of nutrients (nitrite NO_2^-, nitrate NO_3^- and phosphate PO_4^{3-}). The consequences of the resulting benthic fluxes on Arctic Ocean primary production, acidification, and ultimately, atmospheric greenhouse gas emissions are still unquantified. The magnitude and evolution of these SSPF-derived fluxes are highly dependent (i) on the apparent reactivity of the organic matter and (ii) on the response of the resident, reactivating microbial communities in their changing habitat (frozen to thawed sediment).

Here, we present a novel model framework to quantify CO_2, CH_4, and nutrient benthic fluxes from 1900 to 2300 under different SSPF thawing scenarios. The model integrates observational and experimental data from three SSPF cores collected in the Laptev Sea. Eight core sections were selected to study the evolution of OM decomposition, microbial dynamics and CH_4-CO_2 production after thaw. We incubated sediment replicas at 4°C and 10°C for a period of one year. Methanogenesis rates were determined from CH_4 and CO_2 accumulation in the headspace. Additionally, nutrient and carbon cycling dynamics related to OM decomposition were explored through enzyme assays for extracellular leucine aminopeptidase, phosphatase, and β-glucosidase at different timepoints during the incubation period. The incubation data reveals the resident microbial community is immediately responsive to the transition from a frozen to a thawed environment, consuming OM as soon as the sediment is thawed. Through an integrated model-data approach, we will provide microbially informed predictions of SSPF-derived carbon and nutrient benthic fluxes on a local and regional scale.

Exploring Holocene climate history and alpine landscape evolution from rock glacier dynamics: Mt Sopris, CO, USA

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Keywords: rock glacier, Holocene

Despite their ubiquity in modern alpine landscapes of the American West and elsewhere, rock glaciers are little understood. Here we document the modern speeds and constrain the ages of rocks on the surface of a prominent rock glacier in Colorado's West Elk mountains. The glacier is moving at an average of less than 1 m/yr including at its toe where its steep rocky snout is moving into the forest. Ages of rocks on its surface, which record the time at which rock fell from the 300 m headwall, increase steadily from its head to about 13000 years at the terminus. A numerical model that can reproduce these features requires that snow be added to the avalanche cone that feeds the rock glacier in three pulses over this time, each of which generates a down-glacier moving wave of motion. The latest of these is now arriving in the terminus region. The delivery of rock required to create the 2 m thick layer of rock atop the rock glacier and keep the underlying ice from melting implies a headwall back-wearing rate of 4 mm/yr. This is far faster than down wearing of the summit, implying the mountains are eroding sideways.

Participatory permafrost research: the citizen science project "UndercoverEisAgenten"

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Keywords: mapping, Arctic, lowland permafrost, citizen science, outreach

The Arctic is undergoing significant change. Some alarming impacts are more visible, such as decreased ice sheets and sea ice, and others seem to have a more direct impact on people in Central Europe, like landslides or rockfall in the Alps due to permafrost warming. However, thawing of Arctic permafrost is mostly taking place in the hidden depths of the ground and nevertheless has a huge impact on greenhouse gas emissions and livelihoods of people living in the Arctic.

The "UndercoverEisAgenten", funded by the Federal Ministry of Education and Research (BMBF), is testing a novel approach to improve observations on thawing permafrost and refine our understanding in Arctic landscape change with the help of citizen scientists. In 2022 and 2024, students from an indigenous school in Aklavik, NWT Canada, worked together with DLR, HeiGIT and AWI researchers to collect high-resolution aerial photographs from drone flights in the Mackenzie Delta. In close collaboration with secondary schools in Germany, these image data were processed and analyzed in small mapping tasks, so called "micro-tasks". Specifically, we asked students in numerous workshops, school visits and mapathons to mark the center of permafrost ice-wedge polygons – with each image mapped by several students. Results demonstrate that Volunteered Geographic Information data closely matches the actual network structure. Our study shows that using the Voronoi characteristics of ice-wedge polygons can simplify the mapping process, enabling citizen scientists to complete the task with high precision and minimal effort. At the same time the "UndercoverEisAgenten" brought the urgent topic of climate change and permafrost thaw into classrooms and hopefully continued science transfer and discussions on climate change beyond the project lifetime.

More information, teaching material and the mapping application can be also found at: https://undercovereisagenten.org/

Outreach in permafrost research: learnings from communicating to a wider public

Josefine Lenz[1], over the years many contributing colleagues

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Keywords: knowledge transfer, outreach, society, communication

Presenting our findings on scientific level via publications and presentations is an integral part of our scientific work. While teaching in universities and training the next generation of early career researchers seems a natural responsibility in our careers too, sharing our findings and experience with a wider audience is often neglected. However, isn't the society at large where we want to place our discoveries and make humanity transition into a climate-friendly future?

This presentation shows examples of effective science communication within the realm of Arctic permafrost research. Why is permafrost an important element of the cryosphere? What do Arctic permafrost landscapes look like and how are they changing? How to visualize carbon pools? Based on numerous activities with school classes, youth and other audiences, learnings and best-practice cases are discussed – including a live test of outreach materials developed in the dedicated outreach project "Permafrost im Wandel", funded by the BMBF. The presentation will conclude with another step forward in the concept of knowledge transfer: Including citizens into participatory research and why this is a win-win for science and society.

Piezometry in ice-rich permafrost: laboratory and field investigations

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Keywords: rock glacier, hydrology, piezometer, ice-rich permafrost

In 2020, a borehole was drilled into the Schafberg Ursina III rock glacier in the Upper Engadine region of Switzerland and equipped with piezoresistive and temperature sensors (Keller PAA-36XiW level; PT-1000 temperature sensor). These sensors allow continuous, high-resolution monitoring (Bast et al., 2024; Phillips et al., 2023), providing critical insights into subsurface thermo-hydrological processes within the rock glacier. However, the high volumetric ice content complicates data interpretation, as it appears to affect some sensor readings (Phillips et al., 2023).

To address this issue, a series of laboratory experiments were conducted to assess sensor performance in water and ice under controlled conditions. The goal was to develop a method for detecting potential measurement artifacts caused by ice formation near the sensors. In these experiments, the sensors were tested under conditions that mimicked the field environment including sediments and different gravimetric water contents, as well as in tap water, to evaluate their responses to freezing and thawing.

This study combines laboratory and field data from the Ursina III rock glacier to evaluate the limitations of piezoresistive sensors in ice-rich permafrost and explore their potential for accurately monitoring water pressure in sub-zero degree Celsius environments. We will present a methodology developed to identify signals influenced by ice near the sensor, providing a tool for improving the potential of hydrological monitoring in ice- and water-bearing rock glaciers. These analyses aim to improve our understanding of sensor-based hydrological studies in ice-rich permafrost.

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Permafrost and percolating water at Mt. Zugspitze: insights from seismology and DAS

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Keywords: mountain permafrost, seismology, monitoring, Zugspitze

Mountain permafrost degradation due to global warming reduces the stability of steep rock slopes, increasing hazard potential for infrastructure, settlements, and mountaineers. Monitoring these environments continuously remains challenging, but recent studies have demonstrated that seismology can detect both seasonal and long-term permafrost changes with high temporal resolution.

To explore lateral variations in permafrost dynamics at Mt. Zugspitze (German/Austrian Alps), we installed three small seismometer/geophone arrays and a fiber-optic cable for DAS in a tunnel beneath the ridge west of the summit. The seismometers operated for up to two years, while DAS was deployed in campaigns over the same period. We use the cable car operations at the summit as stationary noise sources for cross-correlation calculations, extracting direct and coda waves between the deployment sites and along the fiber-optic cable.

From the seismometer data, we observe significant time-lapse changes in seismic velocity in the western part of the ridge. As freezing begins in fall, seismic velocities steadily increase, but percolating water from snowmelt and precipitation causes velocities to drop again in spring. Despite lower DAS recording quality, preprocessing and cross-correlating with the seismometer data produces high-quality seismic responses. These can be further exploited to pinpoint velocity changes in areas of major freeze-thaw processes, as revealed by electrical resistivity tomography (ERT) studies.

Compared to more traditional methods like ERT, seismology offers both high temporal resolution and spatial insights over larger areas, making it a valuable tool for permafrost monitoring. Its sensitivity to both rock temperatures and cleft water provides additional benefits, as both factors are crucial in permafrost rock mechanics.

Water flow monitoring and geochemistry in high-mountain rockwall permafrost: main results of a 2-year investigation at Aiguille du Midi (3842 m asl, the Mont Blanc massif)

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Keywords: permafrost, hydrogeology, hydrology, geochemistry, high mountain

Water flows in high alpine rock walls play a crucial role in frost weathering, rock fall and rock avalanche triggering, as well as in permafrost dynamics. Yet, the timing and quantity of water running through bedrock fractures, along with their mechanical and thermal implications, remain poorly understood.

Throughout 2022 and 2023, we monitored water flows in the man-made galleries of the Aiguille du Midi (3842 m asl) in the Mont Blanc massif. The monitoring system measured water flow rates, conductivity, temperature and fluorescence. Two different fluorescent dyes were inserted in the snowpack on the rock wall above the galleries during winter to assess water flow timing and source, hydraulic conductivity, and fracture connectivity. Surface temperature measurements were also taken at the rock-snow interface to assess the timing of snow melt, and on the rock surface within and around fractures inside the galleries to detect potential thermal effects of water flows. To decipher potential water origins, we also sampled water to perform geochemistry analyses.

The acquired data provide new insights in water flow characteristics, revealing a seasonal to sub-daily dynamic, and suggest that the collected water mixes snowmelt water, rainfall but also permafrost water.

Quantifying mass wasting from retrogressive thaw slumps on the Qinghai-Tibet Plateau

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Keywords: retrogressive thaw slumps, mass wasting, DEM, ground ice, permafrost carbon

Retrogressive Thaw Slumps (RTSs) are slope failures triggered by abrupt permafrost thaw, occurring in the Arctic and on the Qinghai-Tibet Plateau in regions with high ground ice content. RTSs tend to grow rapidly, posing risks to local infrastructure and releasing formerly frozen soil organic carbon (SOC). The increasing availability of optical RTS inventories and geophysical permafrost datasets, facilitated by advanced machine learning techniques, enables enhanced analysis. By integrating optical and Synthetic Aperture Radar (SAR)-based remote sensing data, we developed a novel method to quantify RTS mass wasting through estimations of material and ground ice loss, as well as associated SOC mobilization.

We utilized single-pass Interferometric SAR (InSAR) from the TanDEM-X mission to generate Digital Elevation Models (DEMs) with a 10 m spatial resolution and approximately 2 m height accuracy for the years 2010 and 2018. RTS annotations derived from high-resolution optical imagery and deep learning defined the affected thaw area, enabling material loss calculations based on difference DEMs (dDEMs). By incorporating datasets on ground ice content, active layer thickness, and SOC content, we estimated the ground ice lost and SOC mobilized due to RTS activity on the Qinghai-Tibet Plateau during the study period.

Typically, RTS annotations based on optical imagery depict the entire geomorphological landform showing vegetation disturbance, while dDEM-based annotations highlight only the actively eroding parts of RTSs. Comparing RTS mass wasting characteristics estimated from manually annotated DEM-based RTS labels with optical annotations revealed high agreement, with deviations of only 5% for volume loss, 12% for ground ice loss, and 13% for SOC mobilization at a test site on the Qinghai-Tibet Plateau.

This new method potentially allows for the upscaling of RTS mass wasting quantification and associated ground ice loss and SOC mobilization to Arctic permafrost regions by combining optical RTS inventories and InSAR-based DEMs.

A database integrating the electrical resistivity data of Switzerland for mountain permafrost spatio-temporal characterization

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Keywords: database, electrical resistivity, monitoring, mountain, ERT

In permafrost research, geoelectrical surveys are increasingly used to detect the presence and extent of permafrost and to characterize its stratigraphy and material composition. When repeated, the resulting temporal changes in electrical resistivity can be related to changes in ground temperature and ice content, and therefore also to ground ice loss over time. However, for financial and logistical reasons, only a few continuous electrical resistivity tomography (ERT) monitoring installations on permafrost exist worldwide. An alternative approach are manual but regularly repeated ERT measurements, such as – besides other examples – in the context of the Swiss Permafrost Monitoring Network (PERMOS). In contrast, there exist many permafrost profiles (estimated to be over 500 in Switzerland) where single ERT measurements have been performed in the past.

In this contribution, we analyze both spatial and temporal variations of the Swiss datasets, which are integrated in the International Database of Geoelectrical Surveys on Permafrost (IDGSP), led by the International Permafrost Association (IPA) Action Group of the same name. Since the launch of the IPA Action Group in 2021, a database has been designed and set up, numerous metadata and data have been collected and homogenized, and public access via a searchable web map is now available (https://resibase.unifr.ch).

The overall goal of the project (supported by the Swiss Geophysical Commission) is to establish a complete database of electrical measurements on permafrost in Switzerland, including ideally all historical measurements. The historical data are re-processed with newly developed filtering and inversion routines and made available to the public to facilitate the repetition of measurements in the context of climate warming-induced permafrost degradation, geotechnical studies of permafrost stability, hydrological studies in the context of natural hazards and water availability from thawing permafrost environments, and serve as a baseline dataset for permafrost distribution and modeling.

New FAIR synthesis datasets on thaw depth, ground ice, and GHG emissions from the Lena Delta region through INTERACT virtual access

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Keywords: FAIR data, data synthesis, thaw depth, ground ice, greenhouse gas emissions

INTERACT (International Network for Terrestrial Research and Monitoring in the Arctic) is an Arctic network of 74 terrestrial field bases (with an additional 21 research stations in Russia on pause) that aims at building capacity for research and monitoring in the Arctic. Alfred Wegener Institute Helmholtz Center for Polar and Marine Research (AWI) was the responsible partner for the Research Station Samoylov Island in the Siberian Lena Delta and coordinated access to the station and the long-term observatories on Samoylov Island as well as to the wider Lena Delta region for international research teams until 2021.

Since the cooperation stop with Russia, we have intensified the compilation and publication of data, which had been acquired in the Lena Delta region for the past >20 years, according to the 'FAIR Guiding Principles for scientific data management and stewardship' through the INTERACT Virtual Access program. These include compilations of:

- thaw depth (TD) measurements of the active layer (AL) based on published and unpublished field data collected during Russian and joint German-Russian expeditions from 1998 to 2022,
- metadata on greenhouse gas (GHG) measurements (in situ, in the lab) based on field work between 1998 and 2021,
- published and unpublished data related to ground ice (ice-wedge ice, intra-sedimentary ice).

The datasets are unique in their spatial and temporal coverage and will be, once published in PANGAEA (https://pangaea.de/), highly valuable sources for future studies related to permafrost thaw, ecosystem changes, climate feedbacks, etc. in the Lena Delta region and beyond.

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Saline tracer tests visualized with 3D time-lapse electrical resistivity tomography for the detection of fractures in bedrock permafrost

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Keywords: time-lapse ERT, tracer test, bedrock permafrost, fractures

Joints and fractures, where large volumes of ground ice can accumulate, play a key role in the thermal regime of bedrock permafrost as they represent a preferential flow path for water and advective heat exchange between the atmosphere and the subsurface. Yet, it is challenging to include them in thermal modeling because their exact location and geometry are commonly unknown. In the Cime Bianche (Aosta Valley, Italy) permafrost monitoring area (highly weathered bedrock plateau) at 3100 m asl borehole temperature measurements and geophysical imaging have shown a high spatial variability in ground temperature and ice content, which suggests the presence of fractured areas affecting the ground thermal regime. We conducted saltwater tracer tests (30–100 l water per injection) at eight different locations at the Cime Bianche site coupled with time-lapse 3D electrical resistivity tomography (ERT) to track the flow of the subsurface amendment and localize flow paths associated to fractured areas. The ERT results show a large difference in flow characteristics between the injection points, even for points in close vicinity (few meters). In five of eight injection points the water infiltrated slowly into the subsurface (over 2–3 hours) resulting in slight conductivity changes over time in the 3D ERT images only close to the injection point. In the other three positions the injected water disappeared after a few seconds resulting in larger conductivity changes, not only directly below the injection point but also to a depth of >10 m, suggesting the presence of fractures. These results demonstrate that our methodology is able to reveal fractures and other preferential flow paths. To further improve the resolution of the resolved fractures more adequate inversion schemes and constraints from complementary data are required.

Rock-ice mechanics in permafrost: extending the Mohr-Coulomb criterion for large-scale failures

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Keywords: alpine permafrost, Rock-Ice Mechanics, Mohr-Coulomb, Shear Experiments

In recent years, large-scale rock slope failures in permafrost regions have been documented, notably at Fluchthorn (Tyrol, 2023) and Piz Scerscen (Graubünden, 2024). Nonlinear fracture mechanics and discontinuum modeling have proven to be promising approaches for simulating these large-scale failures. However, the latter models are not calibrated for the recently observed magnitudes.

This study introduces novel data to extend the Mohr-Coulomb failure criterion for rock-ice failures at high loads. Moreover, we define the brittle-ductile failure transition in permafrost rocks as a function of overload and temperature. Consequently, we propose a law for the ice creep and fracture transition, dependent on temperature, stress, and deformation rate, for permafrost rocks.

To investigate rock-ice failure mechanics, more than 100 shear experiments were conducted at high normal stresses, simulating rock overburden of up to 65 m (1600 kPa). The tests were performed at temperatures ranging from –0.5°C to –10°C, with strain rates consistently maintained at 10^{-3} s^{-1}.

The experiments show that the ductile behavior of ice is primarily temperature-dependent, while normal stress plays a subordinate role. Ductile deformation occurs at temperatures from –1°C to –0.5°C. At colder temperatures, brittle behavior dominates, with two characteristic modes: stick-slip sliding occurs at normal stresses above 400–800 kPa, while single brittle fracture prevails at lower stresses. Ductile material behavior is outside the scope of the Mohr-Coulomb fracture criterion. The integration of this constraint into a conceptual transient thermal model emphasizes the spatially limited applicability of mechanical models to simulate rock slope destabilization.

This study refines the Mohr-Coulomb failure criterion for ice-filled rock fractures by integrating high-load mechanisms and defining the brittle-ductile transition as a function of overload and temperature, offering critical insights for enhancing mechanical models of large-scale permafrost rock slope failures.

Enhanced warming of European mountain permafrost in the early 21st century

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Keywords: mountain permafrost, permafrost temperature, European mountains, warming pattern

Permafrost is observed globally as an Essential Climate Variable (ECV) of the Global Climate Observation System (GCOS). Mountain permafrost constitutes about a third of the global permafrost area and exists at low to high latitudes on both hemispheres. It is characterized by high spatial variability in (sub)surface and atmospheric conditions and large environmental gradients. Mountain permafrost warming and thawing strongly impact mountain ecosystems and communities.

Our study (Noetzli et al., 2024) examines 21st century permafrost warming patterns in European mountains based on a compilation of decadal ground temperature data from sixty-four boreholes collected in the Alps, Scandinavia, Iceland and Svalbard, spanning one to three decades until 2022. The data set has unique spatial coverage with a latitudinal range from 45 to 78 °N and elevations between 275 and 3850 m asl. Observation sites are located in dry bedrock slopes or plateaus, ice-bearing talus slopes and ice-rich rock glaciers.

Measured annual ground temperatures at 10 m depth vary between nearly 0°C and below –6°C. Calculated warming rates at 10 meters depth for the period 2013–2022 exceed 1°C per decade in some cases, generally surpassing previous estimates because of accelerated warming and employing a more comprehensive data set. Substantial permafrost warming occurred at cold and ice-poor bedrock sites at high elevations and latitudes (e.g., mountain sites on Svalbard or above 3500 m asl in the European Alps), at rates comparable to surface air temperature increase. In contrast, latent heat effects in ice-rich ground close to the lower permafrost boundary (such as in many rock glaciers in the Alps) reduce warming rates and obscure important changes in mountain permafrost substrates. The observed warming patterns are consistent across all regions, depths and time periods considered. The future propagation of warming and thawing permafrost to greater depths is largely predetermined already for the coming decades.

Reference:
Noetzli J., Isaksen, K., et al. (2024). Enhanced permafrost warming in European mountains in the 21st century. Nat. Commun., https://doi.org/10.1038/s41467-024-54831-9

Permafrost bedrock under pressure: the hidden hydrology of rockwalls

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Keywords: pressurized water flow, fractured permafrost rocks, repeated electrical resistivity tomography, borehole temperature, piezometric pressure

The role of water flow in promoting and triggering rock slope failures in warming permafrost rocks has increasingly been recognized. Still, quantitative assessments of rockwall hydrology remain scarce due to the competitivity of the processes involved and the challenges of field observations. To address this knowledge gap, we combined timeseries of borehole temperature, electrical resistivity tomography (ERT) measurements, and piezometric pressure observed at the permafrost-affected north flank of the Kitzsteinhorn (Hohe Tauern range, Austria). Ground temperature in two deep boreholes revealed abrupt temperature anomalies and long-term regime changes in the periods 2016–2019 and 2020–2024, indicating the occurrence of non-conductive heat fluxes along fractures. ERT observations conducted at 4-hour intervals in winter 2013, monthly in summer 2023, and daily throughout summer 2024 highlight a massive decrease in electrical resistivity of more than one order of magnitude during the thawing season (July–September), indicating infiltration of snowmelt water into the rockwall. These results coincided with periods of high piezometric levels, indicating pressures up to 1.2 bar above barometric pressure, also suggesting widespread water injection within the fracture network. Our study shows that permafrost rocks are warmed more rapidly by percolating water than possible by slow heat conduction and are subjected to high pressure levels – both critical factors predicting rock slope instabilities and failures.

Lena and Mackenzie river transport, permafrost thaw and coastal waters

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Keywords: Arctic, fluvial, permafrost, coastal, biogeochemistry

We monitored Lena River outflow into the Laptev Sea at our station near the river mouth for over four years, collecting weekly or more frequent samples and analyzing concentrations of major dissolved components. Paired with discharge measurements, these data permitted calculations of fluxes, separation of source waters and detection of seasonal variability in catchment processes. A second monitoring site was established on the Mackenzie River's East Channel, with help of Canadian partners and the INTERACT Transnational Access program. At this site, discharge measurements from Tsiigehtchic, Northwest Territories are complemented by discharge measurements via acoustic doppler profiler at the sampling site.

Data from both monitoring sites are freely and publically available. As a means of shortening the time between analysis, quality control and data publication, and improving access and usage, data from both sites are available via internet dashboards. For both locations, this has created opportunities for additional research groups to introduce measurement parameters to widen the range of catchment processes studied, for example tied to frazil ice formation or how river ice captures and records winter changes in water chemistry. Our next steps include tying these analyses of these data to wider catchment-scale studies, of permafrost thaw upstream of the monitoring site, and downstream in coastal waters out to 20 m water depth. At the Mackenzie River in particular, we coordinate with EU-Canadian cooperations such as the land-to-ocean project (FLOCHAR) and upcoming Beaufort Sea marine work (Arctic Pulse). This contribution describes the monitoring activities, lessons learned so far and the research needs and opportunities that are resulting.

Initiating permafrost research in Bhutan: strategy and first results from the CRYO-SPIRIT project

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Keywords: mountain permafrost, Himalaya, Bhutan

In the Himalayas, thawing permafrost is widely recognized as a major risk for initiating mass movements, influencing hydrological runoff or impacting biodiversity. However, information and knowledge on the occurrence and changes of mountain permafrost in the Himalayas are still very scarce or absent in most areas, such as Bhutan. In the recently launched CRYO-SPIRIT project, Bhutan and Switzerland are joining hands to initiate permafrost research in Bhutan and to fill this important white spot. The project strategy focuses on three main aspects, namely (i) collecting and computing permafrost data using in-situ and remote sensing technologies, (ii) assessing and raising awareness about (future) risks related to permafrost thaw, including the development of adaptation strategies and (iii) building capacity of local researchers to sustain permafrost related monitoring, research and teaching activities in Bhutan.

To assess permafrost, we focus on compiling the first regional map of potential permafrost distribution in Bhutan using in-situ Ground Surface Temperature (GST) measurements and remote sensing-based mapping of permafrost characteristic landforms, particularly rock glaciers. The first CRYO-SPIRIT field campaign took place in autumn 2024 in the vicinity of Thana glacier (Chamkhar Chhu Basin, Bumthang). This site was selected for its proximity to one of the three benchmark glaciers visited annually by researchers from Bhutan's National Center for Hydrology and Meteorology (thus ensuring the long-term continuation of the measurements) as well as for the existence of an automatic weather station and the presence of identified periglacial landforms. During the field campaign, ground surface temperature loggers have been installed between 4300 m asl (below the lower limit of permafrost) and 5200 m asl along an elevation gradient and with different exposition.

In this contribution, we present the results of the first field campaign of the CRYO-SPIRIT project and intend to foster discussions and potential collaborations with international permafrost experts.

Iron redox cycling as controlling factor of the fate of organic carbon in permafrost soils

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Keywords: iron, carbon, redox regime, Greenland, monitoring

Permafrost warms significantly due to climate change, exposing large amounts of soil organic matter to decomposition and releasing substantial amounts of greenhouse gases. Understanding the mechanisms of stabilization and mobilization of carbon (C) is key for the development of earth system models and for climate change mitigation strategies. Iron (Fe) is an important agent in the carbon-climate feedback-loop depending on its oxidation state. Our aim was to quantify the amount of C that is bound to different Fe-species, which differ in their physicochemical stability, and to understand the potential role thereof in a system of degrading permafrost.

We sampled permafrost soils along two environmental gradients from dry to wet conditions on Disko Island, Greenland. Selective iron extractions were applied using four extractants to analyze Fe-phases of different stability, along with C. Furthermore, one gradient has been equipped with soil monitoring stations for year-round measurements of moisture, temperature and redox potential in topsoil and subsoil.

Crystalline Fe was the largest Fe pool. We found more amorphous and less crystalline Fe in the wettest sites, compared to the dry sites. The most C was related to the chelated pools. At the dry sites, around half of the C was bound to Fe. At the wet sites, the relevance of Fe-bound C decreased compared to the dry sites. There, around 20% of the total C was bound to Fe. Records of the redox-regime revealed distinct patterns between oxic and anoxic conditions within the soil, due to alternating soil moisture. The water content of the soils led to an almost winter-long zero curtain, hindering soil temperature to drop below 0°C for 70 days at the driest and for 133 days at the wettest point. The patterns observed underline the importance of long-term measurements and of the timing of sampling

25 years permafrost monitoring in the Swiss Alps

PERMOS[1] and its Scientific Committee

[1]Swiss Permafrost Monitoring Network PERMOS

Keywords: PERMOS, ECV, climate monitoring

Permafrost is classified as an essential climatic variable (ECV) by the Global Climate Observing System (GCOS) due to its sensitivity to climatic changes. The Swiss Permafrost Monitoring Network PERMOS documents the permafrost in the Swiss Alps since 2000 based on long-term field measurements. The monitoring strategy continuously evolved during the past two decades and today includes three complementary elements: (1) direct observation of ground temperatures, (2) permafrost electrical resistivity to determine changes in ground ice content, and (3) rock glacier velocities, which are considered a proxy to assess the thermal regime.

In this contribution, we discuss permafrost conditions in the Swiss Alps during the hydrological year 2024 with respect to the observations of the past 25 years. We observe striking changes in permafrost conditions for all three observation elements. Most recently, the hydrological year 2024 was characterized by a very warm winter resulting from an early snow cover in autumn 2023 following a hot summer. First results point to the warmest permafrost conditions since the start of the observations revealed by all observation elements.

Comprehensive permafrost monitoring in the Canton of Bern

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Keywords: alpine permafrost, monitoring network, borehole temperature, round surface temperature, geophysics

The canton of Bern has established a permafrost monitoring network in the Oberland region. This network includes over 100 sites where surface temperatures, subsurface temperatures, geophysical methods, or a combination thereof have been measured and continue to be monitored. The dataset is unique and includes since 2023, for example, the highest-altitude permafrost borehole in Europe, located near the summit of the Jungfrau at 4140 m asl. A systematic analysis of these data has not yet been conducted.

Massive permafrost rock slide under warming polythermal glacier (Bliggspitze, Austria)

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Keywords: glacier-permafrost interaction, polythermal glacier, permafrost rockslide, rock-ice-mechanical model

Recent studies have brought upon numerous evidence for enhanced rock slope failure from degrading permafrost rock walls. These failures have been thought to be subaerial and triggered by thermal heat propagation from rising air temperatures into the exposed rock faces. However, we have neglected that, at the same time, the dividing line between cold and warm basal states of polythermal glaciers has shifted some hundreds of meters upwards. This means that previously frozen and ice-filled fragmented rock walls under cold glaciers have suddenly and for the first time in thousands of years been exposed to (i) hydrostatic pressures, (ii) warming and degrading ice in fractures, and (iii) rock mechanical degradation in warming rocks. One of the best case studies is the 3.9 to 4.3 million m^3 rock slide at Bliggspitze on 29 June 2007, which detached from a north-exposed, glacier-covered rock slope at 3200 m asl. In this paper, we hypothesize that the transition from cold- to warm-based glaciers, a scarcely observed but widespread phenomenon, caused the massive rock slide. Through intensive analysis of glacier/permafrost evolution and rock mechanical modeling, we demonstrate a new type of rock slope failure mechanism triggered by the uplift of the cold/warm dividing line in polythermal alpine glaciers, a widespread and currently underexplored phenomenon in alpine environments worldwide.

Modeling the thermal dynamics of permafrost talus slopes: insights from a recently destabilized site (Eyjafirði landslide, 6 October 2020, Iceland)

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Keywords: permafrost, hazards, talus, numerical modeling

We present here a paper submitted recently, in which we investigate the Eyjafirði talus slope (Tröllaskagi peninsula, Iceland). This talus is located outside of the climatic boundaries of permafrost. However, a landslide (06/10/2020) originated from the Eyjafirði talus and shows evidence of the presence of ground ice in the source material. Indeed, specific air circulation (the "chimney effect") can occur in the talus, enhancing the persistence of intra-talus permafrost. Hence, the thermal dynamics of the talus is currently poorly understood.

Therefore, we use the software FEFLOW to investigate the permafrost dynamics within the Eyjafirði talus slope from –20'000 years to the present. In our case, FEFLOW uses the finite element method to solve equations of heat transfer within a two-dimensional cross-section of the Eyjafirði talus slope. The thermal boundary conditions of our models are obtained from field temperature measurements acquired in 2021–2022. We test the sensitivity of our model to the initial porosity/ice content of the talus (0.3, 0.5, 0.8), and to the thermal conductivity of the rock phase of the talus and bedrock (0.75, 1.1, 1.75 $W\ m^{-1}\ K^{-1}$).

Temperature measurements show that a chimney effect occurs within the Eyjafirði talus. In our approach, we do not explicitly model the air convection; however, permafrost persists at the base of the talus slope in all modeling scenarios. Increasing the initial porosity/ice content and decreasing the thermal conductivity of the rock phase enhances the persistence of permafrost.

Our modeling approach is unconventional: we initially know that ice was present in the Eyjafirði talus slope at the time of the landslide, which enables additional interpretations of our modeling results. Thus, we can attest that the permafrost dynamics in the talus must be closer to our most ice-conservative scenario – with a thermal conductivity of the rock phase of 0.75 $W\ m^{-1}\ K^{-1}$ and an initial porosity/ice content of 0.8.

Acceleration of the deep-seated permafrost slope instability Wisse Schijen, Southwestern Swiss Alps

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Keywords: deep-seated rock slope instability, slope deformation acceleration, permafrost degradation, water infiltration, long-term monitoring

Wisse Schijen is a >40° steep, NE oriented permafrost slope located around 3000 m asl above Randa in Canton Valais, Switzerland. It was equipped with 8 rows of snow nets for avalanche defense in 1991. These structures have been monitored since 1999 to assess their performance in unstable terrain. Two boreholes were drilled to monitor ground temperature and borehole deformation in 2017 and three in-situ GNSS devices were installed in 2015, 2022 and 2024 to measure slope deformation. The active layer is ca. 2.5 m thick and the permafrost is warming rapidly.

The data revealed a deep-seated instability with significant acceleration and change in deformation regime of the slope in summer 2024. Horizontal displacements exceeded 80 cm in 2024, whereas the previous maximum was 50 cm in 2023. UAV-based photogrammetry confirmed these values. Data from an in-situ meteorological station also measuring ground moisture content in 10 cm depth show that the strongest deformation occurred during snow melt after a particularly snow-rich winter. Subsequent notable accelerations in summer 2024 were triggered by strong rainfall. Analysis of the GNSS data and of borehole deformation data shows that the deformation is occurring in at least two different depths: within the blocky active layer and at over 10 m depth within the rock mass. A flat area with glacier ice and long-lasting snow patches at the top of the slope is a source of water during the warm season, with a small stream disappearing into the top of the unstable slope. Water likely plays a key role in the deformation of this slope and to further investigate its contribution we installed a seismic sensor in the slope in 2022 and are planning to drill piezometer boreholes and carry out geophysical investigations.

Design and installation of a multi sensor in-situ rock slope laboratory in high-alpine terrain

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Keywords: rockfall, rockslide, geology, remote sensing

Landslide processes are a hazard related to steep alpine terrain and are an important driver of alpine landscape evolution. They occur in a wide variety of settings and as a response to various triggering factors. In high alpine terrain processes are strongly influenced by permafrost thawing and glacier retreat driven by climate change. Therefore, rockfall and rockslide processes and activities are studied on a local scale, through the establishment of an in situ rockfall/rockslide laboratory in the Stubaier glacier area in Tyrol (Austria) an area affected by glacier retreat and thawing permafrost at an altitude between 2500 and 3332 m asl Using a multi-methods and multi-sensor approach, we enable long-term monitoring of rock slopes affected by permafrost thawing and glacier retreat. The first measuring instruments were installed in summer 2023 and the complete development is planned for fall 2024. Our approach is based on remote sensing campaigns, geological survey, and meteorological data, we intend to achieve a more complete understanding of the involved processes and their interactions.

Analysing the relationships between environmental parameters that influence carbon turnover in permafrost soils

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Keywords: permafrost soil, organic carbon, microbial biomass

The drastic climate changes in the Arctic are leading to changes in carbon cycling in permafrost soils that are difficult to predict. Mineralization of organic matter (OM) and release as greenhouse gases depends on both the quantity of organic carbon (OC) and its availability for microbial degradation. Key indicator of microbial degradability are OC/N and ratios of labile to recalcitrant organic compounds.

Our study investigates the relationships between different soil parameters and different indicators of OM quality. The data set includes total OC content, OC/N ratio, alkanes and fatty acids (FA) and ratios calculated from this as well as microbial membrane lipids (PLFA) and CO_2 production in incubation experiments. The analyses were performed on samples from the active layer at Svalbard, Siberia, and Greenland, which differ in their climatic conditions and vegetation.

A major difference between sites results from the dense to sparse vegetation cover that is reflected by the OC contents decreasing in the order Greenland > Siberia > Svalbard. Total FA concentrations are related to plant cover in the same way: concentrations are much higher in the densely vegetated soils on Disko Island compared to Svalbard with its sparse vegetation. The non-vegetated Yedoma thaw mounds have very low FA concentrations, so that this parameter is at least a first good reference value for identifying the input of fresh plant material. There is no significant correlation with CO_2 production or PLFA concentration for all sites. These parameters are influenced by the water, OC and N content at all three sites.

Different proxies for OM quality show only site-specific correlation with different soil parameters and demonstrate that it is difficult to find indicators of OC turnover in permafrost soils that are applicable to different locations, because of the complex interaction of various soil parameters and climatic conditions.

Characterizing the distribution and evolution of permafrost in intermediately steep mountain slopes

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Keywords: permafrost, mountain, steep, alpine, thermal

Mountain permafrost, like permafrost everywhere, is warming due to climate change. Knowledge about the distribution of permafrost is relatively advanced for rock faces and debris accumulations – such as rock glaciers, moraine, and scree – but intermediately steep mountain slopes in permafrost zones, roughly ranging from 40° to 60° inclination, remain poorly understood, despite covering a significant proportion of alpine environments. Given the ongoing degradation of permafrost, improving our understanding of its distribution and structure in such slopes is essential. Intermediately steep slopes often feature highly fractured rock, surface debris, and extended/variable snow cover during winter. These slopes may contain more ice than steep rock walls due to increased water availability from the refreezing of snowmelt, resulting in different thermal and morphological responses compared to steep permafrost rock faces. The complex surface micro-topography in these areas leads to substantial variability in solar radiation and snow distribution over short distances, creating highly variable local thermal conditions and resulting in a complex situation regarding the stability of such slopes.

This project investigates four key sites in the Swiss and French Alps: Mont Fort (3329 m asl), Pointes du Mourti (3563 m asl), Cabane de la Dent Blanche (3500 m asl) in the Swiss Pennine Alps, and Sommet de Bellecôte (3417 m asl) in Savoie, France. These sites provide a comprehensive view of permafrost conditions in steep slopes across a variety of high mountain environments.

Our data acquisition and monitoring strategies include:

- Recording of surface temperatures
- Borehole temperature measurements
- Repeated electrical resistivity tomography surveys
- Drone-based structure-from-motion photogrammetry
- Snow depth quantification

This five-year PhD project aims to acquire a substantial field dataset to characterize the distribution of permafrost in steep slopes. As the project progresses, the data will be used to model the distribution and evolution of permafrost in such environments.

Assessing planimetric and volumetric coastal changes on Herschel Island Qikiqtaruk, Yukon, Canada

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Keywords: permafrost, coastal change, erosion, LiDAR, remote sensing

Permafrost coasts in the Arctic are extremely vulnerable to the effects of global climate change. The increase in sea temperature, the decrease in sea ice extent and longer open-water seasons lead to higher coastal erosion. These erosion rates are among the highest worldwide. This results in significant land loss, both planimetric and volumetric, and leads to a notable reshaping of the coastline. Coastal erosion rates are usually reported in 2 dimensions and focus on the shoreline movement. Few studies have attempted to compute the volumes eroded by coastal retreat. The goal of this study is to connect planimetric and volumetric coastal erosion measurements and to serve as an update of coastal erosion rates in the most recent years on Herschel Island Qikiqtaruk (HIQ) in the Western Canadian Beaufort Sea. LiDAR-derived high-resolution digital elevation models (DEMs) were used to compute volumetric data for the years 2013 and 2023. For the planimetric changes we used digitized coastlines derived from satellite imagery in 2000, 2011 and 2022. Our preliminary results show that the average planimetric erosion ranges between –0.71 and –0.74 $m^2\ m^{-1}\ a^{-1}$ for the observed periods 2000–2011 and 2011–2022. The volumetric erosion along the entire coastline of Herschel Island Qikiqtaruk experiences a drastic coastal retreat with average values of –33.18 $m^3\ m^{-1}\ a^{-1}$ whereas the highest values occur along the northwestern, northern and northeastern coastlines of HIQ. This increase can have large implications on the near-shore ecosystems of the island and extensive impacts for the settlement on Herschel Island Qikiqtaruk in the future.

Thermal, hydrological and structural processes responsible for seasonal kinematics of Murtèl rock glacier using borehole data

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Keywords: rock glacier, permafrost creep, seasonal kinematics, borehole data

The Murtèl rock glacier in the Engadin is one of the most investigated rock glaciers in the Alps. In 1987, the first borehole recording temperature and deformation data was drilled, and since then, two more were drilled in 2000 and one in 2015. This thesis will investigate the temperature and deformation from the 2015 borehole to improve the understanding of the thermal, hydrological and structural processes responsible for variations in seasonal kinematic response. Rock glacier deformation data with high temporal and high vertical spatial resolution is rare and valuable to understand creep processes. Rock glacier creep exhibits long-term trends related to mean annual temperatures but also seasonal fluctuations for which the dominant controls are still in debate. The deformation and temperature data from the 2015 borehole will be compared with the on-site meteorological station data, GNSS surface velocity and ground surface temperature loggers for the years 2016–2023. The method developed aims to provide guidance for future systematic analysis of rock glacier borehole data. Two seasonal phases (cold and warm) are defined based on the presence of the insulating snow cover layer. The detection of thermal control happens in the warm phase when the presence of high temperatures at depth leads to late summer acceleration. A warm phase after a snow-poor winter is expected to have warmer permafrost conditions, which favor high deformation rates and vice versa. Hydrological control is defined by the dynamics of the seasonal melt, which is given by the duration of the spring zero curtain. The structural controls are determined by comparing to a similar study of a structurally different Schafberg rock glacier. Improved process understanding of rock glacier creep will help develop more advanced creep models.

Late Quaternary permafrost dynamics of the Beringian land bridge – sediment and ground-ice studies on the Baldwin Peninsula (West Alaska) during spring and summer 2024

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Keywords: paleoenvironment, Westalaska, permafrost sequences

In order to investigate the late Pleistocene permafrost, landscape, and climate dynamics on the eastern side of the Beringian land bridge in the spring and summer of 2024, during the expedition "West Alaska 2024", field studies were carried out on the Baldwin Peninsula. Holocene thermokarst and cover deposits (MIS 1), late Pleistocene Yedoma Ice Complex deposits (MIS 3/2), and older interglacial and glaciofluvial deposits (likely MIS 5e and older) were investigated. This research complements and connects earlier studies across Beringia, i.e., in north-eastern Siberia, on the Seward Peninsula, near Fairbanks, and in the Klondike.

Frozen sediments and ground ice (ice wedges and intra-sedimental pore and segregated ice) were sampled and described. First analyses of the ice content were carried out during the expedition. Analyses of stable water isotopes of ground ice, stable carbon, and nitrogen isotopes of organic matter, age determination (radiocarbon and optically and infrared stimulated luminescence), determination of organic matter composition, analysis of biomarkers, sediment properties, and studies of paleoecology are currently in progress.

Our poster will present field data (permafrost profiles, sediment, and ground ice properties) and first laboratory results from the expedition near Kotzebue on the Baldwin Peninsula. The external conditions during the two phases of the expedition were excellent. We used snowmobiles in spring, as well as boats and four-wheeled vehicles to reach the outcrops in summer. In Kotzebue, we had very good conditions for sample processing and initial laboratory work, including freezer capacity to keep all the samples frozen.

Rock Glacier Velocity (RGV): new parameter of the ECV Permafrost

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Keywords: Rock glaciers, Rock Glacier Velocity, InSAR, GNSS monitoring

Rock glacier motion rates depend on structural, topographic, and climatic factors, while interannual variations are primarily related to those of the thermal state of permafrost. With the objective to provide a novel climate change indicator suitable for mountain permafrost environments, the established parameters of the Essential Climate Variable (ECV) Permafrost, Active Layer Thickness (ALT) and Permafrost Temperature (PT) have been complemented in 2021 by Rock Glacier Velocity (RGV). This context has led to the establishment of RGV Guidelines in 2023 by the Rock Glacier Kinematics and Inventories (RGIK) community.

RGV is an annualized velocity time series documenting the creep rate of mountain permafrost. Time series are derived from various techniques, such as in-situ or remote sensing. Annual ground-based RGV surveys have been undertaken for the past decades in the Swiss Alps on some selected sites, partly in the framework of PERMOS, as well as on a few further rock glaciers in the Alps and worldwide. Air-borne photogrammetry has also been used for longer reconstruction at a multiannual interval. RGV times series mostly show an increasing velocity trend during the past decades. Despite this, methodological challenges to produce consistent RGV time series still need to be overcome. In addition, Synthetic Aperture Radar Interferometry (InSAR) is a satellite-based technique which opens the way to the annual RGV time series production on a large number of sites globally. Within the framework of the ESA CCI Permafrost project, we are analyzing the (dis)similarities between the InSAR-based RGV products and those generated with in-situ surveys and optical remote sensing in order to consolidate the approach

In this contribution, we will present the status of RGV generation, mostly based on GNSS and InSAR data. We will also summarize the research needs for implementing an operational worldwide monitoring of RGV as a GCOS ECV permafrost parameter.

From one lake to two: investigating the evolution and damming mechanisms of proglacial lakes in a glacier forefield in the Swiss Alps

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Keywords: proglacial lakes, ERT, GPR, remote sensing

This study shows the evolution and damming mechanisms of two proglacial lakes situated in a glacier forefield in the Swiss Alps. Initially, the two lakes formed as a single water body at the edge of the Oberferdenglacier, which later split due to the glacier's progressive retreat. As the glacier receded, it left behind a basin that now repeatedly fills with meltwater during the early thawing season. Over the summer, the lake gradually drains, eventually emptying by late summer. To investigate these processes, a combination of Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT), and remote sensing techniques was employed. The aim was to determine whether ice, bedrock, or moraine deposits contribute to the lakes' damming and to understand the mechanisms governing their seasonal drainage patterns. GPR and ERT surveys provided high-resolution imaging of subsurface structures as well as insights into the properties of the damming materials. Remote sensing data from 2018 to 2023 enabled the monitoring of seasonal changes in the lakes, capturing their dynamic evolution in response to glacial retreat. The results indicate that the interplay between permafrost, moraine deposits, and bedrock significantly influences the formation, filling, and draining cycles of these proglacial lakes. This study contributes valuable insights into how glacier retreat shapes proglacial environments and enhances our understanding of glacial lake dynamics, which can aid in assessing potential hazards, such as glacial lake outburst floods (GLOFs), in similar glacial settings.

Sedimentation rates and carbon fluxes on the Canadian Beaufort shelf

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Keywords: permafrost carbon, marine, Arctic Ocean, Holocene

Continental shelves of the Arctic Ocean are undergoing major changes due to global warming. Increased river discharge, deeper permafrost thaw and intensified coastal erosion are releasing large amounts of previously frozen carbon. Despite these changes, sedimentation rates and the amount of permafrost carbon buried on the shelf remain poorly understood. This study focuses on the quantification of sedimentation rates, carbon fluxes and burial processes on the Canadian Beaufort Shelf. Estimating carbon burial is challenging due to the limited availability of data on modern sedimentation rates. The CASCADE database (Martens et al., 2022) provides an average mass accumulation rate of 0.466 g/cm^2/year based on a limited number (n=16) of ^{210}Pb derived estimates for modern sedimentation rates. On longer timescales the spatial variability in carbon burial rates was determined by seismic imaging of Holocene sediment thicknesses (Macdonald et al. 1998), revealing considerable heterogeneity across the Canadian Beaufort Shelf. Therefore, key questions are (1) whether sampling density of modern sedimentation rates sufficiently captures spatial variability across the shelf, and (2) whether the seismically derived Holocene estimates accurately capture modern sediment deposition patterns in the context of ongoing climate change. In fall 2021, sediment cores were taken at 25 sites along five transects on the Beaufort Sea Shelf. Based on measurements of total organic carbon, ^{210}Pb and ^{137}Cs, and the grain density of these cores, sedimentation rates and organic carbon fluxes along the shelf were calculated. By comparing local sedimentation and carbon burial rates, this study aims to improve our understanding of the fate of permafrost carbon on the Canadian Beaufort Shelf.

Organic matter decomposition and greenhouse gas production in thermokarst lake taliks on the Baldwin Peninsula, Alaska

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Keywords: thermokarst, biomarkers, incubation, greenhouse gases, taliks

In the continuous permafrost zone, thermokarst processes are altering and accelerating as the climate changes. Surface subsidence is accelerating and thermokarst lakes are draining, while gullies are expanding and thaw slumps are widening. On the Baldwin Peninsula in West Alaska, such processes are evident and have direct consequences for the local environment as well as the city of Kotzebue. Furthermore, these landscape dynamics have far-reaching effects on biogeochemical cycles, as microbial activity in thawed sediments of thermokarst landforms decomposes organic matter and releases greenhouse gases, further contributing to global warming.

To investigate these processes, sediment cores were collected in March 2024 along two transects that extend from upland areas through thermokarst disturbances into the near-shore zone of the Kotzebue Sound. Taliks were identified and sampled in two thermokarst lakes, a semi-drained lake, and a drained lake basin. These unfrozen sediments are of particular interest concerning organic matter decomposition and greenhouse gas production. A one-year long incubation experiment coupled with pre- and post-incubation n-alkane biomarker analyses on the sediments, aims to decipher organic matter patterns and potentials. First findings from this laboratory work will be presented at the 15th DACH Permafrost Conference.

Numerical modeling and laboratory assessment of thermal stabilization measures for mountain permafrost

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Keywords: permafrost, thermal stabilisation, barrier layer, solar energy, heat pump, cooling pipes, Swiss Alps

Global warming provokes permafrost thawing that can lead to local landscape alteration and damage or destruction of infrastructure. Implementation of protective measures is therefore necessary to avoid incidents and damage. Existing methods for thermal stabilization of permafrost are not directly applicable to the particular conditions of the Alps. Passive techniques generally lack the ability to rapidly and effectively stabilize the soil, while active methods remain costly and are not yet fully optimized. Knowing these challenges, a novel solar-powered thermal stabilization system has been designed. It utilizes both passive and active methods and allows effectively protect Alpine permafrost and the most vulnerable infrastructure built on it from the impacts of global warming. To assess the effectiveness of thermal stabilization system, we conducted numerical simulations using the SNOWPACK model, focusing on the Schilthorn (Switzerland, 2900 m asl) site in Switzerland. In this modeling we performed the various simulations that included the thermal stabilization systems components to evaluate their impact on ground temperature. And the comparison with natural conditions showed the efficiency of thermal stabilization in different combinations. The designed laboratory-scale demonstrator represents the permafrost sample. It includes the components of solar-powered thermal stabilization system components, such as cooling pipes that forms a cold barrier layer, and solar panel that reduces radiative and turbulent heat input, and powers the system. The embedded sensors are monitoring temperature, soil moisture, and heat flux in the permafrost sample. It provides practical insights and study the heat transfer in the sample under different controlled conditions. Results indicate that the barrier layer effectively prevents heat transfer into deeper soil layers, successfully maintaining a frozen layer around the cooling pipes throughout the experiment. Experimental studies, numerical modeling, and optimized engineering allows to design an effective thermal stabilization system for protection of mountain infrastructure.

Thermal and hydrological feedback between boreal forests and permafrost

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Keywords: boreal forest, permafrost, Arctic, land surface modeling, remote sensing

Boreal forests, which cover almost a quarter of the continuous Arctic permafrost, play a crucial role in stabilizing permafrost by regulating heat and water fluxes between vegetation, the ground, and the atmosphere. However, climate change, along with shifts in precipitation regimes, permafrost conditions, forest composition and density, poses a significant threat to this tightly coupled system, potentially disrupting key ecosystem functions.

We investigate how forest cover influences the thermal and hydrological conditions of permafrost using a numerical land surface model called CryoGrid, equipped with a multilayer canopy module. This provides a comprehensive parameterization of fluxes from the ground, through the canopy, up to the roughness sublayer. The implementation of this roughness sublayer allows the representation of different canopy structures and their impact on the vertical heat and moisture transfer. Storyline simulations reveal that forest canopies exert strong control over the ground's thermal regime, primarily through shading, altering snow cover dynamics, and inhibiting turbulent fluxes. These effects collectively cool permafrost, leading to shallower active layers. Furthermore, simulations including excess ice, have shown that forest covers slow ground ice melt by up to 7 years. Forest thereby delays thermokarst formation onset by 3 to 18 years, depending on ice depth and climate scenario, and further provides a significant buffer against extreme weather events.

Changes in forest cover – such as anthropogenic and natural forest loss (through logging, forest fires, or pests), densification, or shifts in dominant species – alter hydrothermal conditions, such as the active layer depth, locally causing either soil drying or wetting. The research underscores the importance of local, detailed models to understand the complex dynamics and highlights how forest disturbances and climate change may lead to significant ecosystem shifts, threatening permafrost persistence and carbon storage across boreal permafrost landscapes.

Investigating carbon contents and fluxes in ice-bearing mountain permafrost

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Keywords: mountain permafrost, incubation study, carbon cycle, past soils, rock glacier

Mountain permafrost research focuses on thermal, physical, kinematic and hydrological processes in response to climatic changes. These environments are believed to contain little organic matter. However, organic carbon could originate from past soils that developed during warmer Holocene periods. Yet, there is a lack of studies investigating if and how carbon is stored and released upon mountain permafrost warming and thawing.

Here, we present in-situ CO_2 fluxes combined with an incubation experiment of ice-bearing permafrost samples examining potential CO_2 release upon thaw. The samples were taken during drilling campaigns in the canton Valais (Eggishorn) and Grisons (rock glacier Muragl), Switzerland. Additionally, substrate samples were collected from the active layer of various rock glaciers in Grisons, at a depth of ca. 30 cm below a layer of rocks. These possibly represent remnants of soils from warmer climates.

In-situ surface CO_2 fluxes were generally negligible but detectable from the substrate in the active layer. In support, first measurements of total organic carbon (TOC) concentrations in unfrozen substrates from the drillings are exceptionally low, ranging between 0.02 and 0.2%. In contrast, first results for the active layer substrate show a TOC concentration of 0.9 to 1.8%. Therefore, we expect C mineralization rates in permafrost samples to be close or beneath the detection limit. Frozen samples will be pre-thawed before filtering alongside the watery samples. The water samples will be analyzed for their chemistry, while the moist substrate samples will be incubated at room temperature. Afterwards, samples will be analyzed for texture, TOC and ^{14}C analysis.

Mountain permafrost is assumed to contain very little organic carbon. Our first results support this assumption, with substrates close to the surface showing the highest TOC concentrations. Laboratory incubation experiments will give insight into the relevance of carbon cycling in future warmer mountain permafrost.

Thawing permafrost in national and international climate policies

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Keywords: thawing permafrost, climate policies, climate action, mitigation

Permafrost is a key component of the Earth's cryosphere and plays a critical role in regulating global climate systems. Recent scientific studies reveal that permafrost thaw is occurring at a faster rate than previously projected. New data also suggest that carbon release from thawing permafrost could accelerate significantly by the mid-21st century. These findings are expected to play a central role in the IPCC's upcoming seventh assessment report. The increasing emissions of greenhouse gases, particularly methane and CO_2, from permafrost regions pose a substantial threat to global climate targets, potentially amplifying warming through a positive feedback loop. However, accurately predicting permafrost carbon emissions remains complex, yet crucial for refining global climate projections and formulating mitigation strategies.

This presentation aims to explore and discuss the intersection of permafrost research with international, multinational, and national climate policies, including the Paris Agreement, focusing on mitigation strategies aimed at preventing unleashed releases of greenhouse gases, irreversible impacts on ecosystems, and socio-economic risks from thawing permafrost. The role of the German Federal Environment Agency (Umweltbundesamt, UBA) in addressing these issues will also be discussed. This includes its involvement in research initiatives, policy recommendations, and collaboration with multinational and international bodies to monitor permafrost regions and promote sustainable climate actions. By addressing both the scientific and policy dimensions, this presentation aims to provide a comprehensive overview of the challenges posed by permafrost thaw and the international efforts to mitigate its impact in the context of global climate governance.

Exploring methane flux dynamics in the upland tundra of West Greenland: insights from two years of field measurements on Disko Island

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Keywords: GHG, methane, Greenland, Arctic upland tundra

Permafrost regions, which are critical to global climate dynamics, are often overlooked as potential methane sinks, with research predominantly focusing on methane-emitting wetlands. This study, conducted as part of my PhD in the so-called MOMENT project, aims to address this gap by evaluating methane (CH_4) and carbon dioxide (CO_2) fluxes in a heterogeneous Arctic upland tundra landscape. Using a portable greenhouse gas analyzer, over 1000 in-situ measurements were collected during the thaw seasons of 2023 and 2024. The research was carried out in the glacial valley Blæsedalen on Disko Island in West Greenland, encompassing three transects along different slope forms with diverse soil-hydrological conditions. In addition, some first flux measurements near a mountain ice cap on a mountain plateau were carried out and parallel, environmental factors such as soil moisture, air and soil temperature, and meteorological conditions were monitored, alongside an extensive soil and vegetation analysis. In my presentation, I will summarize preliminary findings, offering insights into methane flux dynamics and their relationship with environmental variables.

Simple models for mean annual permafrost table temperature and active-layer thickness estimates

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Keywords: permafrost modeling, active layer modeling, TTOP, ground thermal regime

The thermal state of permafrost and the thickness of the active layer have attracted a huge interest over recent decades because climate changes have provoked worldwide permafrost warming and active-layer thickening, with potentially severe consequences for nature and society. Permafrost and active-layer monitoring is therefore of great importance.

Besides temperature, geophysical and/or manual measurements, a variety of models have been developed for estimating the mean annual permafrost table temperature (MAPT) and active-layer thickness (ALT). These tools typically require at least a few ground physical properties as input parameters in addition to temperature variables, which are, however, unavailable or unrepresentative at most sites. Ground physical properties are therefore commonly estimated, which may yield model outputs of unknown validity.

Here, we present two novel and simple analytical–statistical models (ASMs) for estimating MAPT and ALT, which are driven solely by pairwise combinations of thawing and freezing indices in the active layer; no ground physical properties are required. ASMs reproduced MAPT and ALT well in most numerical validations, which corroborated their theoretical assumptions under idealized scenarios. Under field conditions of Antarctica and Alaska, the mean ASMs deviations in MAPT and ALT were less than 0.03°C and 5%, respectively, which is similar or better than other analytical or statistical models. This suggests that ASMs can be useful tools for estimating MAPT and ALT under a wide range of environmental conditions.

Geomorphological mapping of the valley Fremri-Grjótárdalur, Tröllaskagi, Northern Iceland

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Keywords: geomorphology, periglacial processes, glacier-derived rock glaciers, talus-derived rock glaciers, permafrost degradation

Fremri-Grjótárdalur is a hanging valley in the mountainous region of Northern Iceland, on Tröllaskagi, a dissected peninsula within the 'Subpolare Zone' and influenced by a cold maritime climate. Today the valley can be characterized by huge rock accumulation bodies in its cirque, which lies in the zone of recent discontinuous permafrost. Despite numerous attempts to identify and interpret such bodies in Iceland there still is an ongoing debate about their origin as well as the possibility of ice buried beneath their rocky surface and its type.

In combination with the observed increased gravitational mass movements on mountain slopes, the aim of this study is to identify geomorphological features and processes to determine the predominant geomorphodynamics today and in the past to contribute to a better understanding of landscape evolution and inferring likely changes in their nature within changing climate and the issue of permafrost degradation.

The results show that detailed geomorphological mapping can help to determine the current geomorphodynamics of the valley and to identify rock glaciers of various types and origins. As rock glaciers are regarded as reliable permafrost indicators, the recent and past distribution of permafrost was assessed by identifying intact and relict forms. Furthermore, findings were obtained that refute the sole existence of debris-covered glaciers and instead point to the coexistence of glacier-derived and talus-derived rock glaciers of periglacial origin in close vicinity.

However, as geomorphological mapping is limited to the external appearance, it is difficult to draw conclusions about the internal structure of these rock glaciers. It is therefore necessary to use other methods such as geophysics to verify the assumptions made in this study. Due to the increasing gravitational movements in Iceland, it would also be important to focus on so-called molards and other indicators of permafrost degradation in the future.

Progressive failure of a freestanding rock pillar: from precursors to response

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Keywords: rockfall, snowmelt, timeseries analysis, modeling

A freestanding rock pillar with a volume of approx. 20 cubic meters on the Matterhorn Hörnligrat ridge failed on 13 June 2023. Based on comprehensive multi-method monitoring of the pillar and the surrounding ridgeline environment starting in 2008, we perform a detailed analysis of the progressive failure from kinematic precursors to seismic response. The rock pillar was instrumented with a differential GNSS station and inclinometers, showing a strong seasonality in displacement rates and an acceleration with regime change starting in 2022 almost two years prior to the failure. The pillar was in the field of view of a stationary camera, whereby the time-lapse images show a visually apparent acceleration two weeks before the collapse. Seismic precursors and response were characterized employing three seismometers in the vicinity. Weather data as well as permafrost ground temperatures enable us to characterize the temporal variation and identify anomalies at the site. The data analysis suggests that snowmelt water percolating into frozen fractures acts as the main driver for the strong seasonality in displacement patterns observed, eventually resulting in failure. This is supported by controlled laboratory experiments using rock samples from the Matterhorn site and thermo-mechanical modeling.

Capturing the multi-decadal evolution of glacier-permafrost interactions in a high-alpine environment (Ritord, western Swiss Alps)

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Keywords: glacier-permafrost interactions, Swiss Alps, multi-method approach

To better understand the complex dynamics of landforms and their assemblages in environments conditioned by glacial and periglacial processes, this study seeks to foster the use and application of a multi-method and multi-disciplinary approach to capture the multi-decadal evolution of glacier-permafrost interactions in a high-mountain alpine environment. Spatial and temporal surface changes are evaluated on the basis of archive aerial photographs and close-range UAV remote sensing techniques, as well as in-situ GNSS measurements. The long-term kinematic evolution of the landforms within the forefield is investigated with an emphasis on the processes contributing to surface lowering. The evolution of the extent and properties of ground ice and debris-covered surface ice is assessed by geophysical surveys and ground surface temperature measurements.

Our observations indicate a general down-wasting trend among the investigated landforms, including two perennially frozen back-creeping push moraines, a glacier forefield-connected rock glacier, and a debris-covered glacier tongue. The strongest morphological and surface elevation changes, which are partly due to ice melt-induced subsidence, have been observed in areas where glacier ice is present. Furthermore, these changes have been enhanced over the last two decades. A notable decline in resistivity has been documented between earlier (1997) and more recent (2020) geophysical surveys conducted in the push-moraines, the rock glacier rooting zone, and the margins of the debris-covered glacier tongue. This decrease is likely to be the result of an increased water-to-ice ratio due to permafrost degradation, as well as thinning and melting of massive ice from glacial origin. In the debris-covered glacier tongue, resistivity changes are the smallest, which is likely due to its properties, hindering water infiltration within the cold ice body.

Geoelectrical investigations of pingos and related permafrost mounds in the Ogilvie Mountains, northwestern Canada

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Keywords: pingo, ERT, permafrost hydrology, Yukon

Pingos are among the most prominent landforms in Arctic permafrost regions. They exist in a variety of shapes and sizes and are classified as either of hydraulic (open-system in terms of groundwater inflow) or hydrostatic (closed-system) origin. Along with similar-looking features such as palsas, lithalsas or frost blisters, they are commonly referred to as permafrost mounds. In northwestern Canada, apart from numerous hydrostatic pingos in the Inuvik-Tuktoyaktuk coastland area, hydraulic pingos are mainly described for the interior region of Yukon. This study investigates the internal structure of different mounds containing permafrost in order to assess their origin and to discuss their relation to the hydrological pattern and the glacial history of the Ogilvie Mountains. Therefore, Electrical Resistivity Tomography measurements were conducted at mounds of different sizes distributed in two river valleys of the Tombstone Territorial Park, central Yukon. Thousands of data points allow the generation of high-resolution quasi-3D models that can provide multidimensional insights about frozen and unfrozen zones. The results show that not just the outward appearance but also geophysical subsurface properties differ remarkably. In the tallest mound of >20 m height even within the frozen part resistivities vary by up to an order of magnitude reflecting different ground ice characteristics. Here, the central core shows values that are typical for massive ice. Just on the opposite side of the valley, in another mound and the adjacent mountain slope, likely unfrozen low-resistivity zones were found. Those taliks can serve as intra-permafrost water pathways that enable the pingo formation on the valley floor. In this region, periglacial climate conditions, mountainous terrain and permanently changing river channels leading to the formation and drying of oxbow lakes, create environments that might have been suitable for both hydraulic and hydrostatic pingo formation.

Tracing recent herbivory effects on Arctic soil carbon using lipid biomarkers

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Keywords: biomarkers, herbivory, soil carbon, OM storage, land use

Large herbivore activity has shown to influence permafrost temperature and Arctic soil carbon storage, leading to higher soil carbon stocks under heavy grazing influence. However, distinguishing between organic material deposited by the animals, and preserved soil organic matter as a result of lowering soil temperature is difficult, specifically regarding rather fresh material where radiocarbon dating is not possible. We tested measuring lipid biomarkers on Arctic soil samples exposed to various degrees of grazing, both from permafrost and seasonally frozen deposits, looking at n-alkanes and n-alcohols, trying to identify the degree of OM degradation within these samples. Results showed that soil OM was less degraded at sites with heavy grazing impact, more clearly in permafrost-affected deposits. This shows the OM-stabilising effects of lower ground temperatures, as well as a positive impact of large herbivore activity on Arctic soil carbon storage. First implications for future Arctic land use can be derived from this, but a thorough assessment with larger sample sets from circumpolar study sites is advised.

Wetland ages and organic matter storage in drained lake basins of Arctic permafrost regions

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Keywords: peat, radiocarbon dating, carbon, nitrogen, mercury

The age of wetlands in Arctic drained lake basins is a strong predictor of basin ecology and biogeochemical cycling, particularly because of changes in local hydrology over time. Drained lake basins frequently contain peat-forming wetlands, storing large amounts of carbon and nitrogen. Estimations of how thawing and mobilization vs immobilization of permafrost carbon, nitrogen, but also of contaminants such as mercury, contribute to global budgets and should therefore include information on the spatio-temporal distribution of drained lake basins and their age. We present the first database of lake drainage ages covering lowland regions from northern Siberia, across Alaska to the Canadian Arctic. We are using this data to highlight carbon, nitrogen and mercury stocks in a regional subset of the drained lake basins. We cored 124 drained lake basins and used radiocarbon dating of terrestrial peat that formed directly above lacustrine sediments as an estimator of the beginning of post-drainage terrestrial conditions. We assessed the quality of the dates and the stratigraphic, sedimentologic or biogeochemical identification of drainage events for each basin. We then conducted a comprehensive literature study to include > 100 published drainage ages. In this way we will provide a region-wide quantification of drained lakes. We found that nearly all basins drained during the Holocene, and >90 percent of our studied basins drained after 3000 BP. On the other hand, we could prove that individual basins may exist as peat-forming wetlands for many millennia, including wetlands that existed since the late Pleistocene. Our database can be used to quantify carbon and nitrogen stocks as well as mercury stocks in peat from drained lake basins in Arctic lowlands. For the first time, the regional spatial scale and the Holocene time scale will ensure representative information for this highly relevant and abundant permafrost landform.

Mathematical support for seismic snow avalanche risk zoning

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Keywords: snow avalanche, earthquake, risk zoning

Seismic slope processes refer to the interaction between seismic waves and slope stability. As they may be more relevant for snow avalanche triggering than earthquakes, avalanche risk zoning considers information about possible seismic events and is therefore of high importance. To solve this problem, mathematical modeling of physical and mechanical processes in snow and fuzzy sets was applied. The possibility of snowslip occurrence is estimated with the help of information on precipitation, air temperature, the thickness of snow cover, density of snow, angle, and length of slope. In addition, a deterministic methodology for the observation of earthquakes was developed.

Based on the current Canadian Building Code describing the earthquake as a stochastic process, we calculate the earthquake intensity, location, and probability of occurrence. The acceptable probability of an accident death is 0.000001 (Jonkman, 2003). Considering the actual number of seismic avalanche victims, we calculate the acceptable probability of a temblor capable of triggering this hazardous phenomenon by solving this stochastic problem with the Monte Carlo Method. Avalanche risk zoning, based on such an approach, enables the preparation of maps providing an increased safety level and preventing loss of life and property damage.

Reference:

Jonkman S. E. 2003. An overview of quantitative risk measures for loss of life and economic damage. Journal of Hazardous Materials. – A99. – P. 1 – 30.

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