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Big Data for Alpine Glaciology in a Changing Climate

Alpine glaciers are experiencing record rates of melting in recent years due to anthropogenic global climate change. To assess the effects and enable climate adaptation efforts, it is crucial to monitor meltage efficiently and accurately. We develop machine learning models based on UAV data and satellite imagery to assess alpine glaciers and optimize efficacy by experimenting with different deep-learning architectures. The aim is to deploy our models for real-world use, which can yield similar insights for sea ice and polar glacier melting.

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The surprising weather conditions favoring Icestupas

Since 2014, mountain communities in Ladakh, India have been constructing dozens of Artificial Ice Reservoirs (AIRs) by spraying water through fountain systems every winter. The meltwater from these structures is crucial to meet irrigation water demands during spring. However, there is a large variability associated with this water supply due to the local weather influences at the chosen location. This study compared the ice volume evolution of an AIR built in Ladakh, India with two others built in Guttannen, Switzerland using a surface energy balance model. Model input consisted of meteorological data in conjunction with fountain discharge rate (mass input of an AIR). Model calibration and validation were completed using ice volume and surface area measurements taken from several drone surveys. The model was successful in estimating the observed ice volume evolution with a root mean square error within 18% of the maximum ice volume for all the AIRs. The location in Ladakh had a maximum ice volume four times larger compared to the Guttannen site. However, the corresponding water losses for all the AIRs were more than three-quarters of the total fountain discharge due to high fountain wastewater. Drier and colder locations in relatively cloud-free regions are expected to produce long-lasting AIRs with higher maximum ice volumes. This is a promising result for dry mountain regions, where AIR technology could provide a relatively affordable and sustainable strategy to mitigate climate change induced water stress.

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Debris covered glacier mapping and drivers of glacier debris-cover development in the Afghan Hindu Kush Himalaya

Supraglacial debris accumulation influences climate–glacier dynamics and can significantly reduce the sensitivity of glacier mass loss to climate change and so extend the lifespan of glaciers as water resources. Therefore, understanding the patterns and drivers of debris cover glacier is important notably in regions like the Hindu Kush Himalaya where glaciers can be highly debris covered. However, to quantify the extent of debris cover and its evolution through time over large regions remains a challenge. This study developed two Normalized Difference Supraglacial Debris Indices (NDSDI) for mapping debris cover on mountain glaciers based on thermal and near infrared bands of Landsat data for 2016. Both indices were necessary and this reflected geological controls on the extent to which debris cover influenced the thermal signatures of debris-covered ice. As a result of this mapping, a total of 3,408 glaciers were identified which, for those ≥0.01 km^2 in area, gives an ice cover of 2,222 ± 11.1 km^2 and a debris cover of 619 ± 40 km^2, although this varies regionally; regions with smaller glaciers tend to have higher percentage debris cover. To explain the regional variations in this debris cover, we applied principle component analysis to 27 potential drivers. Components that represented variables related to glacier height range and scale (ice area, length, width, and thickness) were uniformly found to be important drivers of debris cover, with those glaciers having the larger in scale have the lowest percentage debris cover. The effects of glacier altitude, were more surprising and interacted with geological controls; glacier altitude was positively-associated with percentage debris cover in chemical organic and detrital sedimentary geological zones; but negatively-associated in igneous and metamorphic geological zones; and we attribute this to different weathering processes.

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Subglacial channels, climate warming and increasing frequency of alpine glacier snout collapse

The retreat of temperate Alpine glaciers has increased markedly since the late 1980s, and is commonly linked to the effects of rising temperature on surface melt. Much less considered are processes associated with glacier surface collapse. A detailed survey of 22 retreating Swiss glaciers suggests that snout marginal collapse events have increased in frequency since the late 1980s, driven by ice thinning and reductions in glacier-longitudinal ice flux. Detailed measurement of a collapse event at one glacier with Uncrewed Aerial Vehicles and ablation stakes showed high rates of vertical ice deformation at the main subglacial channel, the position of which was derived via Ground Penetrating Radar. With low rates of longitudinal ice flux and vertical creep closure, deformation was insufficient to counteract the melt-out of this channel in the snout marginal zone and avoid channel collapse due to melt and block caving. We hypothesize that such channels maintain contact between subglacial ice and the atmosphere, allowing greater incursion of warm air up-glacier, thus enhancing melt from below. The associated enlargement of subglacial channels at glacier snouts leads to surface collapse and the removal of ice via fluvial processes.

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Projection of snow cover in Lombardy Alps under climate change scenarios

The prediction of snow cover under climate change impact is crucial. On the one side snow cover is a key component in the hydrological budget in many areas, and on the other its variability in the last years is undermining the ski tourism and so the economy of many mountain regions. In this study we perform a regional study of the impact of changing climate on seasonal distribution of snow cover of the Lombardy Alps. We partition our study domain in climatic homogeneous areas, according to Aineva (the Italian interregional association for snow-related issues), to evaluate precipitation and temperature gradients. We then use daily series of temperature and precipitation for a control period of 20 years (2002-2021) to feed the hydrological model Poli-Hydro, able to assess the snow cover based on a degree-day approach. We propose a regional analysis to evaluate different degree-day parameters, based on the areas characteristics and we consider the fresh snow compaction with the Martinec equation. The model calibration is performed via two approaches, i) by comparing the modelled snow-covered area with a set of gridded snow cover images acquired by the MODIS satellite, every two weeks during the period 2002-2021, and ii) by using data of daily snow depth of several automatic stations of Arpa Lombardia (the regional agency for the environment) to test the accuracy of the modelled snow depth. Moreover, we collect data of field campaign of snow depth in our study domain in addition to measure of snow-water-equivalent at a basin scale, for several watersheds within the interested area. Finally, we use 6 general circulation models of the latest Sixth Assessment Report AR6 of the IPCC to project future climate and so snow cover until the end of the century.

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Local variability of small Alpine glaciers: Thoula glacier geodetic mass balance reconstruction (1991-2020) and analysis of volumetric variations.

High Alpine environments are rapidly changing in response to climate change, and understanding the evolution of small glaciers is a crucial step in the investigation of future water availability for populations that inhabit these areas. With this study, we present a comprehensive analysis of a small glacier's recent mass balance evolution (1991-2020), located on the Italian side of the Mont-Blanc Massif, where very little previous data were available. To do so, we combined historical data (topographic surveys and LiDAR DEMs of the area) with newly acquired satellite stereo imagery and aerophotogrammetric surveys to obtain multi-temporal digital elevation models (DEMs) of the Thoula glacier (0.52 Km^2). The total ice volume estimation was assessed by accomplishing a GPR survey to investigate the ice thickness and the underlying bedrock. The Thoula glacier shows a significantly lower loss of volume in comparison to other glaciers located in the Aosta Valley region as well as most of the reference glaciers of the Word Glacier Monitoring Service (WGMS) for Central Europe. Particular weather-climatic conditions of the Mont Blanc Massif area, generally characterized by a greater amount of precipitation, could explain the observed differences; however, the present study shows that understanding spatio-temporal local variability of small glaciers can significantly contribute to recognizing different regional and intra-regional patterns of response to climate change.

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Basal thermal regime investigations at Whymper hanging Glacier (Aosta Valley – Italy).

The Grandes Jorasses Massif culminates at 4203m at the Punta Walker summit on the border between France and Italy. The south slope of Grandes Jorasses is widely glaciated and overlies a populated and highly frequented area, the Val Ferret, presenting the main infrastructure being the road in the valley bottom and different hamlets the most important being Planpincieux village. Located at an altitude between 3900 and 4100 m, the Whymper Serac is a hanging glacier that undergoes periodic gravity-driven instabilities. On 1st June of 1998, 150.000m3 of ice fell, and the resulting ice avalanche reached 1750m, at a mere 400m from houses of the Le Pont village and the main Road. The monitoring activity started in 1997: a series of boreholes had been drilled to assess the basal thermal regime of the Serac and subsequently install a monitoring system for failure prediction time. Since then, no other thermal investigation was repeated. In September 2020, three thermistor chains in three different boreholes were installed by means of hot water diesel-powered drill machine on Whymper Serac. Temperature profiles were measured at different intervals during October and November 2020. In September 2021 another three thermistor chains were installed and their temperature profile measured in October 2021. During the same survey, temperature profiles of the 2020 thermistors could be measured again on 2 out of 3 boreholes, (one being too close to the serac front was not safe to reach) confirming data acquired on the 2020 field campaign. The outcome of basal temperature measures of 2020 and 2021 give good spatial coverage of the serac allowing comparison with data from the 1997 measurements. A warming trend of most of the temperature profiles is evident in the comparison of 1997 and 2020/21 data; however, 5 out of 6 points of measure still show negative temperatures. One point of measure shows evidence of temperate ice at the ice/bedrock interface. Most of the Whymper serac gives evidence of being still frozen to the bedrock, but one part of the Serac show what could be the beginning of a transition from cold based regime to temperate based regime. If on one hand surface displacements of the ice mass still show low displacements (typical of a cold based glacier), on the other hand a velocity anomaly was detected on a small portion of the serac corresponding to the temperate based

sector. Further research is needed to better understand the evolution of the thermo-mechanical conditions of the Whymper serac in the actual climate change scenarios. Therefore, thermo-mechanical modeling of the Whymper Serac is underway, based on the Elmer-Ice model.

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Tree isotopic records suggest seasonal importance of moisture dynamics over glacial valleys of the Central Himalaya

Accelerated glacier mass loss is primarily attributed to greenhouse-induced global warming. Land–climate interactions have increasingly been recognized as an important forcing at the regional-local scale, but the related effects on the Himalayan glaciers are less explored and thought to be an important factor regulating spatial heterogeneity. The aim of the present study is a multi-decadal approximation of glacier – hydroclimate interaction over the western region of the central Himalaya (WCH). Multi-species, highly coherent, tree-ring δ18O chronologies from three sites across the WCH were used to derive atmospheric humidity (Atmospheric Moisture Content: AMC) record of the last four centuries. Coherency analyses between regional AMC and glacier mass balance (GMB) indicate an abrupt phase-shift after the 1960s within a common record of the last 273 years. To ascertain the cause of this phase-shift, annual AMC was disintegrated into seasonal-scale, utilizing ~200 years of δ18O record of a deciduous tree species. Seasonal (winter-accumulation: Oct–Mar; summer-accumulation: Apr–Sep) AMC reconstructions and decomposition results indicate a higher sensitivity of regional ice-mass variability to winter moisture dynamics than summer. Over the last two centuries, the relationship between GMB and summer season AMC varied insignificantly. However, despite a decline in Indian summer monsoon (ISM) precipitation after the mid-20th century, the summer season AMC – GMB relation remained stable. We hypothesize that decadal-scale greening, and consequent increased evapotranspiration and pre-monsoon precipitation might have been recycled through the summer season, to compensate for the ISM part of precipitation. However, isotope-enabled ecophysiological models and measurements would strengthen this hypothesis. In addition, high-resolution radiative forcing and long-term vegetation trends point towards a probable influence of valley greening on GMB. Our results indicate that attribution of ice-mass to large-scale dynamics is likely to be modulated by local vegetation changes. We contend that glacier-climate models that account for these processes and feedbacks could reliably improve projections.

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Glacier foreland characterization in Lombardy region, North Italy

Glacier foreland areas are not well known in Alpine area, especially in Lombardy region in the North of Italy. Therefore, the present study intends to provide new and updated information about periglacial zones in this area, focusing on spatial variation in time and surface characterization, taking advantage of a remote approach based on various techniques and materials of remote sensing (e.g., Sentinel-2 and PRISMA satellites). Additionally, updated information about glacier retreats in Lombardy are here reported. As regards glaciers, a reduction of about 30% of area is here detected in the 26 years of study (i.e., 1989-2015), even if the highest retreat is meanly located in 1999-2007 period and the lowest values in the most recent years and no evident trend in time is found. The major loss, both cumulative and yearly rate, is showed by the biggest Italian mountain sectors and a high correlation between glacier extensions and retreat rates are calculated. However, the smallest sectors present the highest cumulative and annual values in percentage (on the total initial area). On the other side, the same results and trends are then detected for foreland progression, which shows a tripled extension from 1989 to 2015. Focusing on glacier-foreland characterization, we mapped four types of surfaces, i.e., bare rock, unconsolidated debris, water and vegetation. Being on average at high altitudes (always > 2000 m), we found a predominance of the first two surfaces. Finally, general aspect dominances for water and vegetation coverages are here detected, with N for water (and generally foreland areas as well) and E for vegetation.

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Nonlinear sensitivity of glacier mass balance to future climate change unveiled by deep learning

Glaciers and ice caps are experiencing strong mass losses worldwide, challenging water availability, hydropower generation, and ecosystems. Here, we perform the first-ever glacier evolution projections based on deep learning by modelling the 21st century glacier evolution in the French Alps. By the end of the century, we predict a glacier volume loss between 75 and 88%. Deep learning captures a nonlinear response of glaciers to air temperature and precipitation, improving the representation of extreme mass balance rates compared to linear statistical and temperature-index models. Our results confirm an over-sensitivity of temperature-index models, often used by large-scale studies, to future warming. We argue that such models can be suitable for steep mountain glaciers. However, glacier projections under low-emission scenarios and the behaviour of flatter glaciers and ice caps are likely to be biased by mass balance models with linear sensitivities, introducing long-term biases in sea-level rise and water resources projections.

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Structure from Motion and Ground Penetrating Radar for reliable mass balance and volume estimation of ice in caves

Permanent cave ice deposits are experiencing significant volume losses worldwide. The increasing melting rates threaten the preservation of these deposits that represent a valuable source of paleoclimatic information. Although scientific community agrees on this, what is missing so far is a proper methodological approach to correctly quantify how much such ice masses are effectively reducing. This study presents a possible solution for the accurate calculation of both long-term mass balance and volume estimation of ice in caves through terrestrial Structure from Motion Multi-View Stereo (SfM-MVS) and Ground Penetrating Radar (GPR). The proposed combination of a photogrammetric and a geophysical technique, offers the opportunity to have a low-cost workflow with very limited logistical problems of transportation and human resources and a fast acquisition time, all key factors in such extreme environments. Under optimal conditions, SfM-MVS allows sub-centimetric resolution results, comparable to more expensive and logistically demanding surveys such as terrestrial laser scanning (TLS). 14 SfM-MVS acquisitions were made between the 2017–2020 ablation seasons in two ice caves of the Canin-Kanin massif (Julian Alps, SE Alps) while 2 GPR surveys were acquired in 2012. The obtained dense point clouds and digital terrain models (DTMs) made possible a reliable calculation of any change occurring inside the scene through the Multiscale Model to Model Cloud Comparison (M3C2) algorithm, and the measurement of the total ice volume losses. The integration of SfM-MVS with GPR surveys provided comprehensive imaging of the ice thickness and volume, proving to be a reliable, low cost, and multipurpose methodology ideal for short to long-term monitoring.

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Radio-echo sounding and satellite observations inform about recent and past processes at the ice-sheet base of Jutulstraumen drainage basin (Antarctica)

Future sea-level predictions require that the history and physical state of the Antarctic ice sheet is well understood and constrained by observations. Much of the ice sheets' ice-dynamic properties are governed by processes at the ice-bed interface which can be imaged with radar sounding surveys. Moreover, certain processes at the ice-sheet base can have an effect all the way to the ice surface, which in turn can be observed with satellites. Here we use a combination of ultra-wideband radio-echo sounding data, satellite radar and laser altimetry data to characterize the evolution of the subglacial morphology of the Jutulstraumen drainage basin (western Dronning Maud Land, Antarctica). Based on the classification of the bed topography, we reconstruct the step-by-step modifications the subglacial landscape has experienced since the beginning of the glaciation of Antarctica, 34 million years ago. In addition, between 2017 and 2020, we find evidence of active episodic cascade-like subglacial water transport along the subglacial valley network. The combination of these observations will represent an important step towards a better understanding of large-scale ice-sheet dynamics in western Dronning Maud Land.

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The Glac-UP system

Glac-UP is a project carried out by a group of four friends, who desire to contribute to the safeguarding and enhancement of Alpine Glaciers. To do so, they envisioned a system to raise awareness on the issue of global warming and to foster high-value local projects, to benefit specific glaciers. Glac-UP system involves individuals, corporations, local communities, local authorities and scientists. In August 2021, Glac-UP S.r.l. Benefit Corporation was incorporated. Glac-UP is committed to raise awareness on the issue of melting of Alpine Glaciers, the triggering factor, the main consequences and the need to adopt a sustainable lifestyle. Instagram, Facebook and Glac-UP newsletter serve as our major channels to raise awareness. Along with the awareness raising commitment, Glac-UP fosters high-value local projects that benefit specific Alpine Glaciers. The first project we support has to do with the active protection of an Italian Glacier. Glac-UP serves as a promoter and facilitator of high-value projects, to benefit specific mountain areas. Through the so-called 'Glac-UP system', all the relevant actors are involved: individuals, sponsoring corporations, local communities, local authorities and scientists. Glac-UP is innovative in the way individuals and sponsoring corporations are engaged in these projects: they can thus 'Adopt a Glacier', to support the initiatives we foster. Glac-UP is open to any contribution about projects that can bring a positive impact on Alpine glaciers.

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Three different glacier surges at a spot: What satellites observe and what not

In the Karakoram, dozens of glacier surges occurred in the past two decades, making the region one of the global hotspots. Detailed analyses of dense time series from available optical and radar satellite images revealed a wide range of surge behaviours: from slow advances with slow ice flow over periods longer than a decade to short, pulse-like advances with high velocity over a few months. In this study, we present an analysis of three glaciers that are currently surging in the same region of the central Karakoram: North Chongtar, South Chongtar and an unnamed glacier referred to as NN9. Various optical (e.g. Landast, Sentinel-2, Planet) and SAR satellite sensors combined with DEMs from different points in time (e.g. SRTM, SPOT, HMA DEM) are used to (1) obtain comprehensive information about the evolution of the three surges between 2000 and 2021 and (2) to compare and evaluate capabilities and limitations of the different satellite sensors to observe surges of comparably small glaciers in steep terrain. We found a contrasting evolution of advance rates and flow velocities for the three glaciers, while the elevation change patterns are more similar. Advance rates >10 km y-1, velocities up to 30 m d-1 and surface elevations raised by 200 m are derived for South Chongtar and a slow, almost-linear increase of advance rates (up to 500 m y-1), flow velocities below 1 m d-1 and elevation increases of up to 100 m for the three times smaller North Chongtar Glacier. The even smaller glacier NN9 shows a mixture of the surge behaviour of the two other glaciers. It seems that different surge mechanisms are at play in this region and that the mechanism can change within a single surge. We also found that sensor performance is dependent on glacier characteristics (size, flow velocity, amplitude of changes). Flow velocities could not be derived from Sentinel-1 for any of the glaciers. All considered DEMs have sufficient accuracy to detect the mass transfer during the surges and elevations from ICESat-2 ATL03 data fit neatly.

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3D Modelling of Debris-Covered Glaciers

Debris-covered glaciers react differently to external forcings than clean-surface glaciers. They show inherent glacier length fluctuations without any variations in climatic forcings as the debris layer impact the glacier mass balance. Based on Mayer and Licciulli (2021), we couple the full-Stokes equation with debris transport, but extend the model setup to 3D. The framework is implemented using the Ice-Sheet and Sea-level System Model (ISSM).

Reference Mayer C and Licciulli C (2021) The Concept of Steady State, Cyclicity and Debris Unloading of Debris-Covered Glaciers. Front. Earth Sci. 9:710276. doi: 10.3389/feart.2021.710276

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Investigating snow melt at a high alpine glacier plateau

Snow melt on glaciers during the early melt season is responsible for water percolations and a change of the thermal conditions in the snow pack. Runoff from the snow pack on glaciers is controlled by water content and the water routing. In dependence of the conditions, large amounts of melt water can be released during short periods. We investigate the dynamics of melt water generation by combining detailed field investigations with modelling the physical processes in the snow pack for Vernagtferner in the Ötztal Alps, Austria. For this we use a combination of in-situ monitoring of the physical conditions in the snow pack, the meteorological forcing and a physically based model for the temporal evolution of the snow pack. With this setup it is possible to investigate, not only the waxing and waning of the snow cover over a season, but also the detailed processes, which lead to water discharge on the pixel-scale.

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A long range permanent TLS system at Hintereisferner (Austria) – possibilities for glacier mass balance measurements

A permanent long-range terrestrial laser scanning (TLS) system is installed at Hintereisferner, Ötztal Alps, Austria to investigate snow cover dynamics at high-resolution. Glacier mass balance measurements are available since 1952/53 at Hintereisferner. The measurements are traditionally done with the glaciological mass balance method, but the interpolation of the 10 to 50 measurements leads to concomitant uncertainty in the mass balance. A TLS acquires >1 point/m² and can improve the mass balance measurement, as more knowledge is acquired on processes that happen on the glacier surface. Even though, this method integrates all processes that lead to area-wide surface height changes, i.e. the surface, internal, and basal mass changes, daily TLS acquisitions give insight on processes such as snow fall and snow drift. An uncertainty assessment has been done for the TLS, which includes uncertainties caused by the atmosphere, scan geometry and the mechanical precision of the TLS. We show the possibility to measure snow drift and compare the glaciologial measurements with the data acquired with the TLS.

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Reconstruction and numerical simulation of ice avalanches from the Grandes Jorasses glaciers (Italy)

The Whymper Serac, a cold hanging glacier at the South-West face of Grandes Jorasses (4208 m), on the Italian side of Mont Blanc massif, has been the source of various ice avalanches during the past decades, causing fatalities among alpinists. We analyse the dynamics of five well-documented ice avalanche events in the period 1993-2020, using a combination of empirical equations relating the angle of reach to the ice avalanche volume with the software tools r.randomwalk and r.avaflow. Thereby, we build on experiences from former analyses on the adjacent Planpincieux Glacier. r.randomwalk simulations are performed with back-calculated angles of reach for each of the five events. The basal friction angle used in r.avaflow is optimized for correspondence with the observed impact area and runout distance, individually for each event, in order to reconstruct plausible flow velocities and energies. In contrast to ice avalanches from the Planpincieux Glacier, the angles of reach of ice avalanches from the Whymper Serac cannot be predicted by published empirical relationships, most likely due to the very steep topography (near-vertical rock face) and the complex avalanche patterns, including splitting into at least two branches. We have therefore built a separate empirical volume-angle of reach relationship from the empirical data for the Whymper Serac, yielding a generally good correspondence with one outlier, resulting in an R^2-value of 0.66. However, more work will be necessary to understand the key determinants for the dynamics and mobility of ice avalanches from the Whymper Serac before extrapolating the empirical relationship to larger volumes and performing forward simulations of possible future scenarios.

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FAU Glacier Portal: Freely available Sentinel-1 glacier velocities data base

Changing climate conditions significantly influence the state and dynamics of glaciers world wide, leading to implications for global sea level rise, freshwater availability and geomorphologic hazards. Ice dynamics and mass flow variations can globally be monitored by long- and short-term changes in glacier surface velocity. Consistent and continuous information on glacier surface velocities are important parameters for time series analyses, numerical ice dynamic modelling and glacier mass balance estimations. Thus, glacier surface velocities are defined as an Essential Climate Variable (ECV) by WMO for the polar ice sheets, but should be monitored on a regular and global scale also for other glacier systems. The Sentinel-1 constellation as part of the EU/ESA's Copernicus program is acquiring repeat-pass Synthetic Aperture Radar (SAR) data since 2014. It enables global, near real time-like and fully automatic processing of glacier velocity fields at up to 6-days repeat cycle, independent of weather and solar illumination conditions. We present a new near-global database of glacier surface velocities derived from Sentinel-1 imagery. It comprises continuously updated image pair velocity fields, as well as monthly and annually averaged velocity mosaics at 200 m spatial resolution. We apply intensity feature tracking on both archived, new and upcoming Sentinel-1 acquisitions available from the ASF Archive. The products cover all major glaciated regions outside the polar ice sheets and is generated at a HPC (High Performance Computing) environment at the University of Erlangen-Nuremberg. The velocity products and metadata are freely accessible via an interactive web portal (http://retreat.geographie.uni-erlangen.de) after registration. It can be for downloaded and simple online analyses can be performed. We give information on the procedures of data generation, as well as on how to access the data and demonstrate the capabilities of our products for velocity time series analyses at very high temporal resolution.

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GLOF hazard assessment by hydrodynamic modelling: a case study in Bhutan

The frequency of glacial lake outbursts floods (GLOFs) is likely to increase with the ongoing glacier retreat, which produces new proglacial lakes and enlarges existing ones. We simulate the outburst of a potentially dangerous glacial lake in Bhutan by hydrodynamic modelling. Although the lake volume is known, several parameters connected to the dam breach and the routing of the flood are rough estimates or assumptions, which introduce uncertainties in the results. For this reason, we create an ensemble of nine outburst scenarios. The simulation of magnitude and timing of possible inundation depths is an important asset to prepare emergency action plans. For our case study in the Mo Chu River Basin, the results show that, even under the worst case scenario, little damage to residential buildings can be expected. However, such an outburst flood would probably destroy infrastructure and farmland and might even affect the operation of a hydroelectric powerplant more than 120 km downstream the lake. Our simulation efforts revealed that, by using a 30-m elevation model instead of a 5-m raster, flood magnitude and inundation areas are overestimated significantly, which highly suggests the use of high-resolution terrain data. These results may be a valuable input for risk mitigation efforts.

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Detection of potentially highly crevassed areas by a minimum of geometric information – a parameter based approach on Vernagtferner

Crevasses pose severe risks for mountaineers and field glaciologists. Smaller cracks between 0,5 and 2 m are still dangerous, but often not visible on medium resolution satellite imagery. If they are snow covered, they are completely undetectable by optical sensors. We try to develop an approach to detect potentially crevassed areas by a minimum of geometric data, making the method transferable to other areas. On Vernagtferner, we compared a reference dataset of observed crevasses with the curvature of the ice surface and the change in driving stress. Both parameters can be derived from a DSM (digital surface model) and a model of the bedrock, derived from ice thickness measurements. Certain correlations could be observed, showing that crevasses preferably form in convex areas and in areas where the driving stress rapidly increases. This is in agreement with the theory of crevasse formation. Although larger parts are still misclassified, the approach has a potential for the definition of probably uncrevassed areas and for the planning of safe routes.

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Hydrological modelling in support of studying retire of alpine glacier. The case of study of Forni glacier, in Italian Alps of Valtellina.

Forni is a main glacier of Valtellina, in Lombardy region of Italy, and it is up to now the most extended glacier of the country, and thus, one of the most studied: change in area, mass balance, ablation, dynamics, albedo, surface temperature and snow accumulation data were measured/estimated along the years. From the tongue of the glacier Frodolfo river originates, which is mainly fed by Forni during summer.Frodolfo,as a major tributary of Adda river, provides a significant amount of water for hydropower, agriculture and civilian use. As a consequence, current Forni glacier retire has impact not only on mountain tourism but also on water resources management in the region. To link glacier retire and Frodolfo regime with a physical model it is necessary rely on hydrological modelling. Here we used Poli-Hydro hydrological model to assess Forni retirement and snow/ice melt water contribute to seasonal discharge through 1995-2021, using as input data climate data by Automatic Weather Stations (AWS) (1 directly on Forni glacier), initial glacier volume, that we estimated measuring glacier area in 1994 using airborne images, and spatializing ice thickness using empirical parametrization, which was then validated with Ground Penetrating Radar and Airborne Echo Sounding measurements. Snow melt was calibrated using AWS and validated using high resolution Sentinel images, while to calibrate ice melt we used ablation stakes data and spatialized albedo values assessed with LANDSAT 7 ETMS sensors. Unpublished data from high altitude hydrometers of Idrostelvio network (2010 to present) are finally used to validate discharge data output. The model here calibrated and validated can be used to study and project glacier retire, and Frodolfo discharge, in climate change scenarios.

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Constraining regional glacier thickness estimates with retreat observations in the European Alps

Due to global climate change, mountain glaciers are retreating in many regions. Accurate knowledge on the volume of glaciers is essential in order to assess future glacier evolution, melt-water runoff, and the resulting natural hazards. Yet, in-situ thickness observations are limited to a relatively small number of glaciers worldwide. A potential remedy is found in the increasing number of available remote sensing data, such as glacier inventories and digital elevation models (DEM). Using this information on glacier area retreat data, past thickness observations can be derived in a straightforward way from glacier inventories to identify deglacierized areas at the glacier margin. Thereafter, the former ice thickness on those areas can be interfered by subtracting respective DEMs. In spite of this remote sensing information, it is known that an uneven distribution of thickness observations across the glacier domain can result in a significant bias in the estimate of the total ice volume. Here we show an approach to overcome this generic limitation of so-called “retreat” thickness observations by applying an empirical relationship between the ice viscosity at locations with in-situ thickness observations and observations from DEM-differencing at the glacier margins. We combine various data sets on glacier area, elevation and thickness. Therefore, we use observations from the European Alps, which exhibit one of the densest glaciological measurement networks. Initially, the ice thickness distribution in the 1970s of the Swiss and Austrian Alps is estimated, based on all available in-situ observations of glacier thickness, as well as based on thickness in the previously glacierized areas alone, to derive topography-based correction factors of the ice viscosity. Eventually, our results are compared to recent glacier thickness and volume estimates by transferring the approach to all glaciers of the Alps and reconstructing the total ice volume of the reference year 2000.

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Using artificial moulins to characterise englacial R-channels

The englacial and subglacial drainage system exerts key controls on glacier dynamics. However, due to its inaccessibility, it is still only poorly understood and more detailed observations are important, particularly to validate and tune physical models describing its dynamics. By creating artificial glacier moulins -- boreholes connected to the subglacial drainage system and supplied with water from surface streams -- we present a novel method to monitor the evolution of vertical, pressurised, englacial R-channels. From tracer and pressure measurements we derive time series of the hydraulic gradient, discharge, flow speed and channel cross-sectional area. Using these, we compute the Darcy-Weisbach friction factor, obtaining values which increase from 0.1 to 13 within five days of channel evolution. Furthermore, we simulate the growth of the cross-sectional area using different temperature gradients. The comparison to our measurements largely supports the common assumption that the temperature follows the pressure melting point. The deviations from this behaviour are analysed using various heat transfer parameterisations to assess their applicability. Finally, we discuss how artificial moulins could be combined with glacier-wide tracer experiments to constrain parameters of subglacial drainage more precisely.

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Evidences of Bedrock Forcing on Glacier Morphodynamics

It is well known that bedrock geometry influences glacier surface morphology. Nevertheless, in mountain glaciers, quantitative evidence is rare. In our research, we investigated the Planpincieux Glacier (NW Italy) from a helicopter using a 25 MHz dual-polarization ice-penetrating radar. We measured the ice thickness and detected the bedrock topography underneath the glacier. Furthermore, we used digital photogrammetry to survey the glacier surface morphology and kinematics. Through helicopter-borne structure-from-motion and aerial LiDAR, we acquired a solid image every year between 2014 and 2019 and two solid images in 2020. Digital terrain analysis evidenced the presence of recurrent crevasses, with constant position across the years (variation between 6-14 m, on average). Such crevasses delimited distinct kinematic domains, identified using digital image correlation. Bedrock and glacier topography presented out-of-phase correlated undulations that approximately fit a sinusoidal function of different amplitude, with the crevasses occurring 40±8 m downstream bedrock steps. These observations directly demonstrated the bedrock topography strong influence on the glacier surface morphodynamics. Additionally, we surveyed the morphological evolution of a large unstable sector that menaced to break off in the last years, thus representing a serious threat for the population. Ice avalanches run-out simulations have been conducted according to different hypothetical collapsed volumes. Therefore, a precise quantitative estimation of the involved ice was necessary. This was obtained using ice-penetrating radar data and manual delineating of the unstable sector on the solid images. The results showed that the ice thickness has remained approximately constant since 2014 (i.e., ~25 m at the end of the ablation season), while its area has roughly halved (from ~23000 m2 to ~12000 m2). On the other hand, the ice thinned by approximately 5 m between 20 July and 8 September 2020 and this sector lost more than 30% of its volume. This finding demonstrates that high-frequency morphology monitoring is essential for correct glacial hazard assessment.

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Towards an Alpine landscape without glaciers – full of lakes?

Ongoing climate change is causing glaciers to retreat rapidly. Our landscapes are changing as a result, and the question about what the newly-emerging spaces might offer is increasingly attracting attention. Here, we present an assessment on the number and size of new glacier lakes that will emerge in the Swiss Alps until the end of the 21st Century. We advance upon previous, similar assessments by (i) relying on a recently released, Country-wide subglacial topography that is based on an unprecedented collection of ground penetrating radar data, (ii) estimating the timing by which individual glacier lakes will emerge, and (iii) estimating the rate by which these lake will disappear again, due to sediment input from the deglacierizing areas. Especially the latter is a point that was never addressed so far.

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Progress in resolving surface mass balance patterns in the Pamirs from remote sensing

In recent years, regional and global glacier models scales have shown increasing skill at reproducing glaciological and geodetic observations of mass balance. However, the relatively few monitored glaciers poorly represent the diverse characteristics manifest at a regional scale, such as avalanching and supraglacial debris cover. Geodetic measurements partially reduce these problems by providing a superb target for model calibration, but can lead to parameter equifinality. Remote sensing observations show promise to mitigate this problem by providing high frequency model targets (e.g. on-glacier albedo values, snow coverage, and melt extent). Flux divergence estimation methods provide additional possibilities to constrain the altitudinal patterns of mass balance over several-year periods. Their utility has previously been demonstrated for quantifying the melt-suppression of supraglacial debris, for example. Here, we estimate specific mass balance across the Pamir mountains of Central Asia for the 2015-2019 period, making use of an improved continuity-based flux divergence approach. We compare these results to end-of-season glacier albedo patterns and selected high-resolution imagery, and demonstrate the method's ability to represent selected glacier accumulation areas affected by sustained avalanche mass inputs and preferential snow deposition, despite uncertainty. These inferences of mass balance mechanisms are particularly important in this region, where glaciological measurements and scarce and geodetic observations remain moderately uncertain. Our results highlight the utility of the continuity approach for providing a modelling target for mass balance patterns on large, unmonitored glaciers, and for constraining secondary glacier mass balance controls.

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Investigating the deeper internal stratigraphy of alpine glaciers using a phase coherent radar

The internal structure of glaciers contains information about past snow accumulation rates and ice flow patterns. Internal reflection horizons (IRH) can also act as isochrones for the intercalibration of the age-depth relationship of ice cores. IRHs are typically observed by radio echo sounding, whereat deeper layers are often difficult to resolve with classical pulsed radar systems. Using phase coherent radars, this former echo-free zone (EFZ) could be unveiled at the polar ice sheets, showing folding, buckling and disruptions in the ice stratigraphy. The heavy ground-based and airborne radar systems used at the ice sheets are, however, not suitable for deployment in alpine environments. In order to investigate the EFZ of an alpine glacier (Colle Gnifetti, Switzerland/Italy), we mobilised the lightweight autonomous phase-sensitive radio-echo sounder (ApRES) in combination with a GNSS used in real time kinematic (RTK) mode. This setup allowed antenna repositioning with sub-wavelength accuracy, which satisfies the criteria to apply synthetic apperture radar (SAR) processing to the phase-coherent data. Using this method, we are able to image the layering in the former EFZ. The obtained radargram covers the sites of two ice cores (Ice Memory and KCC). In addition, the ice fabric orientation was measured using radio-polarimetry to study how glacier flow is affected by the anisotropic ice rheology.

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How did the IGS survive the pandemic

I will give a brief overview of how we did during the pandemic, how we adjusted, what we did to keep contact with our member and continued to engage with them and how we are emerging from it.

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Multispectral and thermal UAV surveys of the Zebrù glacier (Ortles-Cevedale group)

In this contribution, we will present results from the Unmanned Aerial Vehicle (UAV) surveys operated at the Zebrù glacier (Ortles-Cevedale group, European Alps). The aim of this study is to map the surface features (i.e. broadband albedo, liquid water, impurities, surface temperature) of an Alpine glacier from multispectral and thermal sensor at high spatial resolution. Zebrù glacier is a typical Alpine valley glacier, located in the Ortles-Cevedale group in the Southern Rhaetian Alps (Central Italian Alps, Italy). The UAV surveys were conducted using two lightweight UAV on the ablation zone of the glacier on 29 and 30 July 2020. A DJI Mavic 2 Pro equipped with a Hasselblad L1D-20c camera was flown to acquire RGB images to generate high spatial resolution orthophoto and digital surface model (DSM) of the glacier ablation zone through structure from motion algorithms. The camera was set with a focal length of 10.26 mm, while the other parameters (shutter speed, aperture range and ISO) were set in automatic mode to optimize the image brightness in such a heterogeneous context. Furthermore, a DJI Matrice 210-RTK quad rotor with interchangeable payloads, dual payload carrying capability and a pre-installed RTK positioning system was flown with a XT2 thermal camera (Flir) and a lightweight multispectral camera MAIA S2. The MAIA S2 instrument features nine sensors operating in distinct wavelengths of the VIS/NIR electromagnetic spectrum region. It has been calibrated using reflectance measured over four panels with a HandHeld Analytical Spectral Devices (ASD) Field Spectrometer. Validation has been carried out using field spectra measured over various glacial features at 17 different locations. The multispectral mosaic of the glacier was classified with a support vector machine (SVM) algorithm. Classes were defined as: snow, clean ice, melting ice, dark ice, cryoconite, dusty snow and debris cover. Several parameters were calculated from the nine spectral bands of the MAIA S2 sensor, and maps were produced. For the different classes, those parameters were then compared with surface temperature derived from the XT2 thermal camera. We found the SVM algorithm capable of distinguishing different materials present on a glacier surface. The validation scheme revealed an overall classification accuracy of 76% and a kappa coefficient of 0.70. Furthermore, a significant correlation was identified between surface temperature and the thickness of the debris cover on the glacier.

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Long-term evolution and present conditions of a large rock glacier system at Bjørneø Island, SW Greenland

Research on active rock glaciers in Greenland has been focussed so far primarily on Disko Island and Zackenberg located north of latitude 69°N. Based on regional permafrost models, widespread existence of permafrost and therefore potentially active rock glaciers are also possible further south in Greenland. To work on this question research on a large rock glacier (size: 1 km²; elevation 250-600 m a.s.l.; NNW-exposed) at 64°30'N on the island of Bjørneø near the capital Nuuk was initiated in 2016. Different fieldwork-based and desktop-based (remote sensing and modelling) research has been carried out since then. In our presentation we will give an overview of these activities.

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Do the temperature index models provide a linear response of annual mass balances to air temperature and precipitation?

The temperature index models are generally used to simulate the surface mass balances of glaciers from temperature, precipitation and potential solar radiation. These models have been used to simulate the glacier wide mass-balances of numerous glaciers over the 20th century and in the future. In a recent publication, the sensitivity of glacier mass balance models to climate warming was questioned; the authors claim that the response of glaciers to climate change is not linear and conclude that temperature index models are not approriate to simulate the evolution of glaciers in the future. Here, we performed numerical experiments to analyze the sensitivity of degree day models to air temperature and snow precipitation.

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Girls on ice Austria

Inspiring Girls Expeditions has a long history of taking small groups of girls into a challenging and inspiring mountain environment with the aim of allowing the young women to develop their full potential as creative thinkers and citizens. The program targets girls who – for a broad range of reasons – might need a boost and an inspirational experience at this point in their lives. We offer guidance for critical thinking, problem solving and facing new challenges alone and as a team. This proves arms the girls with confidence, experience and personal and professional growth opportunities that will linger on after the program is over.

Girls on Ice Switzerland operates a German and French glacier expedition annually and in 2021 the first Girls on Ice Austria expedition was successfully run. These European branches train female early career scientists in mentoring and field education practices, and give an opportunity to develop the organisation within the wider global volunteer network. We believe that this program plays a part in increasing diversity of leadership and scientific thought within the field of glaciology.

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A centennial perspective of glacier-climate change in West Greenland

Greenland's ice masses are currently experiencing particularly strong changes due to human-induced climate change. The observed time series of atmospheric conditions and impacts on the glacier surface are limited to recent decades. A longer perspective is particularly important if we are to achieve realistic reconstructions of the past or modeling of the future, but is usually limited to indirect proxies. In this contribution we present the motivation and our plans for the recently granted project 'WEG_RE - Centennial Climate Drivers of Glacier Changes in Greenland'. We follow an interdisciplinary approach with the aim to improve our understanding between glacier changes and the underlying climatic drivers. The project is based on archival data from the legendary expedition of the Graz-based researcher Alfred Wegener in the years 1929-1931. During this ambitious expedition climatological and glaciological data were collected, which are excellently documented and available in the archives of Graz University. Climatologically, the period is are of particular relevance because they were at the core of a short warm phase in which air temperatures were similar to those currently observed. Moreover, they are available at a temporal resolution that is unique for the time. Almost a century later, we will therefore again monitor the same parameters over three years at exactly the same measurement sites and under similar atmospheric conditions, albeit under fundamentally different geometric boundary conditions. We will expand the monitoring to include modern methods based on artificial intelligence and innovative process studies. Using modeling and deep learning approaches, patterns will be compared and feedback mechanisms quantified on a local scale. Dynamic models are then used in a next step to perform sensitivity studies. This allows us to determine which factors are causing the observed changes and how glacier surface and atmosphere influence each other. This will give the results further spatial relevance, as the geometric configuration of the study area is representative of large parts of the Greenland ablation area. An important component of the work will also be the interaction and involvement of the Greenlandic people. We will be logistically supported by local operators and at the end of the project the results of the research will be presented in the neighboring settlements. Further outreach activities beyond the core project are already planned and there are possibilities for synergies with other projects.

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Seasonal evolution of supraglacial lakes on Baltoro Glacier from 2016 to 2020

The existence of supraglacial lakes influences debris-covered glaciers in two ways. The absorption of solar radiation in the water leads to a higher ice ablation, and water draining through the glacier to its bed leads to a higher velocity. Rising air temperatures and changes in precipitation patterns provoke an increase in the supraglacial lakes in number and total area. However, the seasonal evolution of supraglacial lakes and thus their potential for influencing mass balance and ice dynamics has not yet been sufficiently analyzed. We present a summer time series of supraglacial lake evolution on Baltoro Glacier in the Karakoram from 2016 to 2020. The dense time series is enabled by a multi-sensor and multi-temporal approach based on optical (Sentinel-2 and PlanetScope) and Synthetic Aperture Radar (SAR; Sentinel-1 and TerraSAR-X) remote sensing data. The mapping of the seasonal lake evolution uses a semi-automatic approach, which includes a random forest classifier applied separately to each sensor. A combination of linear regression and the Hausdorff distance are used to harmonize between SAR- and optical-derived lake areas, producing a consistent and internally robust time series dynamics. Seasonal variations in lake area are linked with the Standardized Precipitation Index (SPI) and Standardized Temperature Index (STI) based on air temperature and precipitation data derived from the climate reanalysis data set ERA5-Land. The largest aggregated lake area was found in 2018 with 5.783 km2, followed by 2019 with 4.703 km2, and 2020 with 4.606 km2. 2016 and 2017 showed the smallest areas with 3.606 km2 and 3.653 km2, respectively. Our data suggest it is a warmer spring seasons (April-May) with higher precipitation rates that lead to increased formation of supraglacial lakes. The time series decomposition shows a linear increase in lake area of 11.12 ± 9.57 % per year. Although the five-year observation period is too short derive a significant trend, the tendency for a possible increase in supraglacial lake area is in line with the pronounced positive anomalies of the SPI and STI during the observation period.

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A new initative to present the cryosphere monitoring in Austria to stakeholders and the Public

Climate change particularly affects the cryosphere (snow, glaciers, permafrost). As an alpine country with a relevant occurrence of the cryosphere, Austria is particularly affected by climate change and the decline of the cryosphere, with clear impacts on the economy (e.g. lack of snow for tourism, flood events, droughts). Therefore, appropriate measurement programs have been developed in Austria to monitor the changes in the cryosphere.

The funding of the cryosphere monitoring programs in Austria are rather fragmented (e.g. motivated the different roles of the cryosphere for stakeholders in Austria) and likewise the processing and presentation of the measured variables are rather different and partly uncoordinated. Moreover, the benefit from an overall perspective on the cryosphere, which includes the snow cover, the permafrost and the glaciers together, is not achieved. Despite the rather extensive measurement program of the cryosphere in Austria, this makes the cryosphere changes quite difficult to understand for the public, administration but also for international interested parties.

The initiative "Cryosphere Monitoring Austria" (KryoMoAT), funded by the Austrian Federal Ministry of climate protection (BMK) has therefore set itself the goal of filling this gap and, for the first time, presenting and making available all climate-relevant measurements on changes in the Austrian cryosphere in a targeted form for stakeholders (including research) and the public. This initiative includes in particular the networking of the community, standardization and harmonization of the measured variables and jointly coordinated presentation of the monitoring. In order to maintain this beyond the project period, a strategy paper for the long-term provision of periodic reports on the state of the Austrian cryosphere will be developed.

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Atmospheric sounding of the boundary layer over alpine glaciers using fixed-wing UAVs

The turbulent exchange of heat and moisture between the lower atmosphere and glacier surface is a crucial component of the glacier surface energy balance. However, relatively little is known about the microclimate of mountain glaciers, the local wind systems, and the structure and dynamics of the atmospheric boundary layer over alpine terrain. Since the pioneering glacio-meteorological experiments with a tethered weather balloon on the Pasterze Glacier (Austrian Alps) in 1994, no further vertical soundings of the atmospheric boundary layer over alpine glaciers have been performed, probably because of the high costs and logistical efforts. Unoccupied Aerial Vehicles (UAVs) equipped with meteorological sensors are a flexible and low-cost alternative to conventional weather balloons, but their suitability and potential for atmospheric sounding in the mountains has not yet been explored. Here we present the results from four separate UAV measurement campaigns on the Kanderfirn in the Swiss Alps during the ablation season 2021. We sounded the lowest 400 m of the atmospheric boundary layer over the Kanderfirn with a self-built fixed-wing UAV at two-hour intervals to investigate vertical changes in air temperature, humidity, wind speed, and wind direction in the course of a day. The most prominent observations over the glacier were the diurnal variation of the lapse rate (from minimum 5°C km^{-1} during the night to 9 $°C^{-1}$ during the day), the general increase in humidity from morning to evening, the prevalence of a katabatic glacier wind in the lowest 50-100 m, and the frequent development of a pronounced valley wind above. The successful glacio-meteorological experiments on the Kanderfirn illustrate the potential of low-cost UAVs for 3D atmospheric sounding in complex alpine terrain and serve as a basis for similar applications in other areas.

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On the use of high resolution web map services for mapping Little Ice Age glacier extents

As glaciers are an indicator of climate change, extending the record of glacier variability into the past improves our understanding of their current behaviour as well as projections of their future response to climate change. Until recently, glacier extents have mainly be mapped using multispectral satellite images (e.g. Landsat, Sentinel-2) with manual corrections.With the increasing availability of web map services (wms) such as the ESRI imagery service or national services, the situation has strongly changed as orthorectified very high-resolution images are now available for digitization of geomorphologic features such as glaciers.

In this study, which is performed in the framework of the EU Horizon 2020 project PROTECT (protect-slr.eu) we present (1) a workflow for mapping Little Ice Age (LIA) glacier extents using the ESRI wms, (2) a detailed uncertainty analysis and (3) first results of glacier area changes since the LIA for selected regions in Alaska, Baffin Island, Novaya Zemlya and the tropics. Additionally, we used Sentinel-2 images, the ArcticDEM and modern glacier outlines from the Randolph Glacier Inventory (RGI), among others. Geomorphological indicators and glaciological considerations were considered to guide the digitizing. The possible timing of the former LIA maximum extents was obtained from the literature, but here large uncertainties remain.

In total, outlines for 489 LIA glaciers were created and compared to today, yielding relative area changes of -20%, -15%, -26% and -61% for Alaska, Baffin Island, Novaya Zemlya and the tropics, respectively. We conclude that wms such as the ESRI World imagery layer provide, despite their shortcomings, an excellent opportunity to precisely map LIA maximum extents of glaciers around the world.

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30 years of surface snow accumulation measurements at Neumayer station, Antarctica

Surface mass balance is one of the key glaciological variables to determine the present state and future evolution of an ice mass under global climate heating. In particular in Antarctica, surface mass balance is still insufficiently know. Given the size of the ice sheet direct observations or reconstructed values from firn and ice cores are sparse. Indirect satellite remote sensing methods either provide only an integral view of the mass balance (e.g. from gravity missions like GRACE), observe the total change of surface elevation or, like passive microwave observations, come along with considerable uncertainties.

With the end of the year 2021 a 30-year record of surface snow accumulation at the German Neumayer overwintering stations has been completed. The data were recorded at approximately fortnightly intervals at the stake farm of the "Pegelfeld Süd“. This provides us now with a time series over a standard climate period which can be used investigate the interaction of surface accumulation with other environmental properties like temperature, wind, sea ice cover and alike. Moreover, it can be used validate other products, e.g. from remote sensing or regional climate modelling. The surface accumulation data are complemented by less regular density measurements as well as a second stake farm established in 2009 at the Neumayer station III. We will present first and preliminary result of the annual evolution as well as seasonal characteristics of surface accumulation.

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Age-depth distribution at the Beyond EPICA deep ice-core drill site and influence of the basal ice unit on dynamic behavior

Two key elements for the adequate description of ice-sheet flow are basal sliding and internal deformation. Current models assume that the ice sheet slides over bedrock at any point where basal conditions are temperate and deforms internally mostly in the lower part of the ice in regions where the bed is frozen. So far, however, it has been unclear how shear deformation takes place and if and how stagnant ice influences ice dynamics. Very high frequency (VHF) Ground Penetrating Radar (GPR) can now be used to image the full thickness of more than 2.5 km in high resolution, allowing us to investigate how its thickness affects dynamic behavior of the ice sheets by analysing internal layer architecture. Based on a high-resolution GPR data set obtained in 2019 during the Beyond EPICA – Oldest Ice pre-site survey, we present evidence that the lowermost part of this region of the Antarctic ice sheet, several 100 m thick, is most likely stagnant. This means that this basal unit of the ice body, and hence basal sliding, should not be included as a dynamic active layer in modeling. Preliminary results from analysis of GPR data from Little Dome C in East Antarctica indicate that adequate including modeling of the basal unit would better describe the age-depth distribution of the ice sheet.

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A glacier group within the TEAMx (Multi-scale transport and exchange processes in the atmosphere over mountains) programme and experiment?

Atmospheric processes specific to mountainous regions heavily affect the exchange of momentum, heat and mass between the Earth's surface and the atmosphere. TEAMx is an international research programme that aims at improving our understanding of these processes (http://www.teamx-programme.org/). The purpose of this talk is to determine if there is interest in this Alpine Glaciology Group in making a glacier group within the TEAMx network.

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Occurrence of microplastics on glaciers from Northern and Southern hemisphere

Microplastics (MPs) are considered as a hot topic in environmental studies because of their presence in every ecosystem worldwide, as well as their potential toxicity towards organisms. A growing number of monitoring studies has demonstrated the occurrence of MPs in every ecosystem worldwide. However, the information of the MPs contamination of high-mountain ecosystems, including glaciers, is still limited. The present work aimed at investigating the presence of microplastics on five glaciers around the world, namely the Midtre Lovénbreen (Svalbard, Norway), the Longyearbyen (Svalbard, Norway), the Steindalbreen (Northern Norway), the Iver (Chile) and the Exploradores (Patagonia, Chile) glaciers. In 2019, the supraglacial debris was collected along the ablation tongue of these glaciers. MPs were isolated from the debris and identified through Fourier Transformed Infrared (FTIR) microscopy (μ-FTIR). Overall, independently of the glacier, a total of 34 MPs were isolated, 20 (58.83%) were fibres and 14 (41.17%) were fragments or particles. The abundance of MPs ranged between 0.02 and 0.12 MPs/g dry weight, but no significant differences occurred among glaciers. The polymeric composition of the MPs was dominated by polyethylene terephthalate (29.41%), followed by polyester (11.76%), polypropylene (11.76%) and polyethylene vinyl acetate (11.76%). Grouping the MPs per category of polymer, polyester (42%) was predominant in the contamination pattern, followed by polyolefin (26.5%) and polyvinyl ester (23.5%). Our results showed the occurrence of MPs on glaciers from both the hemispheres and suggest the necessity of further in-depth studies to investigate the sources, the fate and potential impact of such contamination in remote areas.

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Microplastics contamination of supraglacial debris differs among glaciers with different anthropic pressure

Contamination by microplastics (MPs) is a global issue involving different terrestrial and aquatic ecosystems, in both densely populated and remote areas. Nonetheless, to date the information on the presence and the distribution of MPs in high-altitude ecosystems, including glaciers, remains incomplete and disjointed. This study aimed at investigating the occurrence, the spatial distribution, and the contamination pattern of MPs within and among three glaciers with different anthropic pressure. Samples of supraglacial debris were randomly collected from glaciers in the Ortles-Cevedale massif (Central Alps, Northern Italy), namely the Forni, the Cedec and the Ebenferner – Vedretta Piana glaciers. MPs were isolated and characterised in terms of shape, size, and polymeric composition. The mean concentration (± SE; MPs/g dry weight) of MPs measured in debris from the Forni, the Cedec and the Ebenferner glaciers was respectively 0.033 ± 0.007, 0.025 ± 0.009, and 0.265 ± 0.027 MPs/g. MPs abundance and pattern of contamination observed in the debris from the Ebenferner glacier, which suffers a notable anthropic pressure due to the presence of a ski area, significantly differed from those of the other glaciers, with a higher abundance of MP fragments compared to the other glaciers where fibres were, instead, prevalent. Moreover, no significant spatial gradients in MPs distribution were detected along the ablation areas of the glaciers. Our results suggest that local contamination can represent a relevant source of MPs in glacier ecosystems subject to high anthropic pressure, while long range transport can be the main source on other glaciers.

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Mountain glacier biodiversity show temporal and spatial trends at a global scale

Glaciers are ecosystems hosting active and dynamic microbial communities. Together with ice sheets, they have been recognized as a biome in their own right but their biodiversity is still almost unknown.. In the last years, we have investigated the diversity mountain glaciers on the Alps, Andes, and Karakoram mountains focussing on the bacterial communities of cryoconite holes, small ponds full of melting water with sediment at the bottom present on the surface of glaciers that are considered hotspots of biodiversity in these environments. Our results are disclosing the biogeographical patterns of cryoconite community composition as well as the ecological processes shaping their structure. Although cryoconite bacterial communities share a similar core microbiome worldwide, their community structures differ among glaciers and among geographical areas. Cryoconite communities also show a temporal trend along the ablation season. However, cryoconite hole communities on the same glacier, albeit changing during each season and between years, are more similar to one another than those on different glaciers, even nearby ones. Finally, an analysis at the global scale, suggests that glacier bacterial communities can be ordered along with global trends, that may be driven by the glacier size as well as by biogeographical patterns. These studies are therefore shedding light on the biodiversity and the ecological processes of this still neglected biome.

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Surge glaciers and associated hazards in the Karakoram

Glaciers in the Karakoram exhibit irregular behavior as compared to central and eastern Himalayan glaciers. Terminus fluctuations of individual glaciers lack consistency and, unlike other parts of the Himalaya, total ice mass remains stable or indicate a slight increase since the 1970s. These seeming anomalies are addressed through a comprehensive mapping of surge-type glaciers and surge-related impacts, based on multiple satellite images, glacier surface displacement, digital elevation models, ground observations, and archival material since the 19th century. We identified about 220 surge glaciers and documented about 150 ice-dammed glacier lake outburst floods (GLOFs) by 30 glaciers in the Karakoram. Surge cycle timing, intervals and mass transfers are unique to each glacier. Active phases range from some months to > 15 years. Surge intervals are identified for 27 glaciers with two or more surges. The ice-dammed lakes are generated through the barriers made by the advancing/surging glaciers. This differs from Himalayan GLOFs highlighted recently, attributed to climate change with rapidly retreating or thinning glaciers and mainly originate due to the failure of moraine dams. Some detailed case studies (Kumdan group of glaciers and Shispare) of surge history and associated ice-dammed GLOFs in the Karakoram are presented. We also discussed the possible impact of climate change on Karakoram glacier surges and associated ice-dammed GLOFs.

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Aufeis: A neglected cryosphere component in the Trans-Himalaya of Ladakh

Meltwater from the cryosphere is vital for water supply and livelihood security in the Trans-Himalaya. While many studies focus on glacier and snow cover changes, *aufeis* – a different component of the cryosphere - is largely neglected. *Aufeis* is a seasonal ice body, which is created by successive overflow of water on frozen surfaces (icing process) and mainly occurs along rivers and streams. It stores winter base flow and persists throughout the melting period in spring supplementing river discharge during spring and early summer. It has been described for North America and Siberia, but comprehensive investigations on *aufeis* formation in the Trans-Himalayan region are still in an exploratory phase (Brombierstäudl et al., 2021), although the phenomenon is used by the local population for the construction of ice reservoirs (Nüsser et al., 2019).
In this study, the endorheic Tso Moriri basin is selected for mapping and quantifying *aufeis*. The spatial and temporal patterns and the hydrological importance for the regional high-altitude wetlands is analysed. In order to classify *aufeis* with a Random Forest classifier, , remote-sensing data from the Landsat and Sentinel-2 missions are used for the time-period from 2008 to 2021.
In total, 27 frequent to regular occurring *aufeis* fields with an average maximum extent of 9 km² were identified which are located at a mean elevation of 4700 m a.s.l. The temporal patterns revealed two distinct phases, an accumulation phase, lasting from November until, and a melting phase from May until July. The study shows that icing is highly variable on the intra- and inter-annual scale and it is spatially heterogeneous throughout the basin. Furthermore, water sources feeding *aufeis* are often located close or within wetland areas. Although largely vegetation is absent on areas which are subject to regular *aufeis* formation, locations of water sources, *aufeis* fields, and wetland distribution suggest close hydrological interactions.

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Multi-temporal elevation changes of Fedchenko Glacier, Tajikistan (1928-1958-1980-2010-2017-2019)

Fedchenko Glacier, located in the central Pamir in Tajikistan, is the longest glacier in Asia. Due to its prominent location and its large size, it attracted scientific interest over the course of the twentieth and twenty first centuries, providing thus a rare legacy of historical data in Central Asia. In this study, we investigate a series of topographic data from 1928 to 2019. We use topographic maps collected during historical expeditions in 1928 and 1958. We take advantage of modern satellite data, such as KH-9 spy satellite (1980), SPOT5 (2010) and Pléiades (2017 and 2019). We also rely on ICESat campaign of 2003 and numerous GNSS surveys conducted in 2009, 2015, 2016 and 2019, which ensures a proper co-registration of the satellite data.

We calculate a mean rate of elevation change of -0.40 m/yr for 1928-2019, with a maximum thinning at the lowermost locations (approaching -0.90 m/yr). Despite this long-term thinning trend, we observe large contrasts between the sub-periods. The thinning rate of the tongue doubled for two sub-periods (1958-1980 and 2010-2017) compared to the long-term average. The ERA5 reanalysis (1950-2020) and the Fedchenko meteorological station records (1936-1991) reveal a dry anomaly in 1958-1980, followed by a wet anomaly in 1980-2010, which might have compensated for the temperature increase and thus mitigated mass losses. This wet anomaly could be an important feature of the "Pamir-Karakoram" anomaly, characterized by limited glacier mass losses in this region during the early twenty-first century. Our work contributes to better constrain the decadal glacier thickness changes, with unprecedented temporal resolution. This opens the way for more sophisticated approaches that link the glacier response to climate variability over decades.

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Dry and wet snow: snow line altitudes in Upper Hunza, Pakistan

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Layer geometry as a constraint on the physics of sliding onset

Transitions from basal no slip to basal sliding are a common feature of ice sheets, yet one that has remained difficult to observe. In this study we leverage recent advances in the processing of radar sounding data to study these transitions through their signature in englacial layers. Englacial layers encode information about strain and velocity, and the relation between their geometry and the onset of basal sliding has been demonstrated in ice flow models (the so-called ``Weertman effect"). Here we exploit this relation to test the long-standing hypothesis that sliding onset takes the form of an abrupt no slip/sliding transition. We present results from the Institute Ice Stream in West Antarctica, where the observed layer geometry does not support an abrupt no slip/sliding transition. Our findings instead suggest a much smoother sliding onset, as would be consistent with temperature-dependent friction between ice and bed. We close by discussing how targeted field work on suitable alpine glaciers could advance the understanding of sliding onset physics.

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Towards understanding catchment hydrology: an application of a temperature index-based coupled surface/subsurface hydrological model in Stok catchment, Ladakh Himalaya

The Himalayan snow and ice melt provides water for irrigation, hydropower generation and domestic consumption to the downstream regions. Therefore, it is important to gain an understanding of the amount, timing, and temporal pattern of the melt contribution from these sources. In this study, we attempt to understand the hydrology of a small catchment (Stok) of the cold-arid Ladakh region. Snow and glacier meltwater of this catchment is the only source of water to the entire village of ~300 households (~1500 people) as per Census of India 2011. The methodology of this study involves the use of satellite, in-situ and reanalysis datasets to estimate the flow using Temperature Index-based coupled surface/subsurface hydrological model. The modelled surface flow was further calibrated using the in-situ discharge of two summers (2018 and 2019). In addition, the specific contribution from snow, glacier and rainfall to the total flow was also investigated.