10th EARSeL Workshop

Remote Sensing of the Cryosphere:

Methods and Applications from Regional to Global Scale

February 6 - 8, 2023
Bern, Switzerland

EARSeL

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CLIMATE CHANGE RESEARCH

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European Association of Remote Sensing Laboratories

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Swiss Academy of Sciences (SCNAT)

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Laupenstrasse 7

3008 Bern - Switzerland

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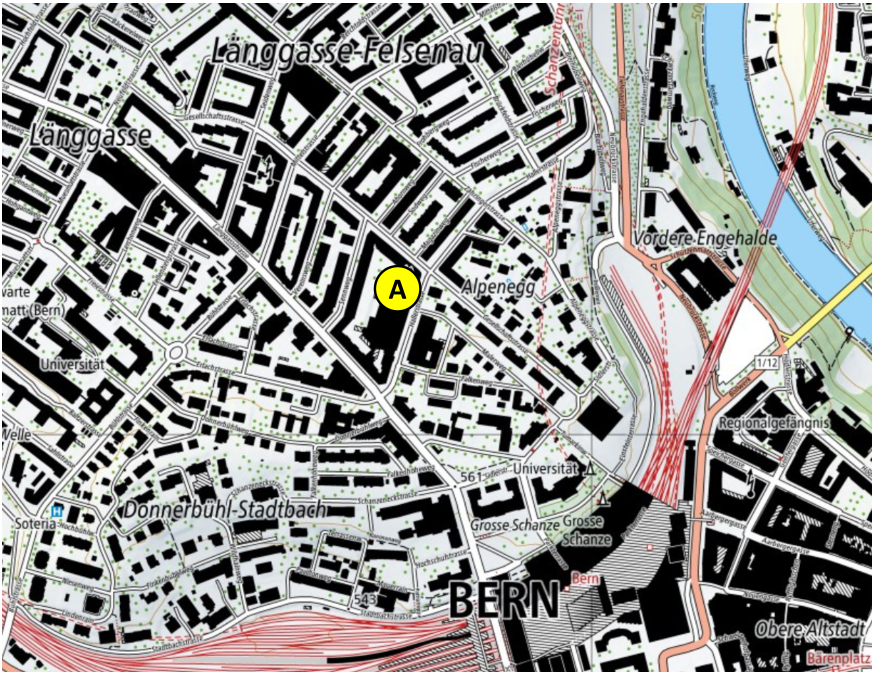
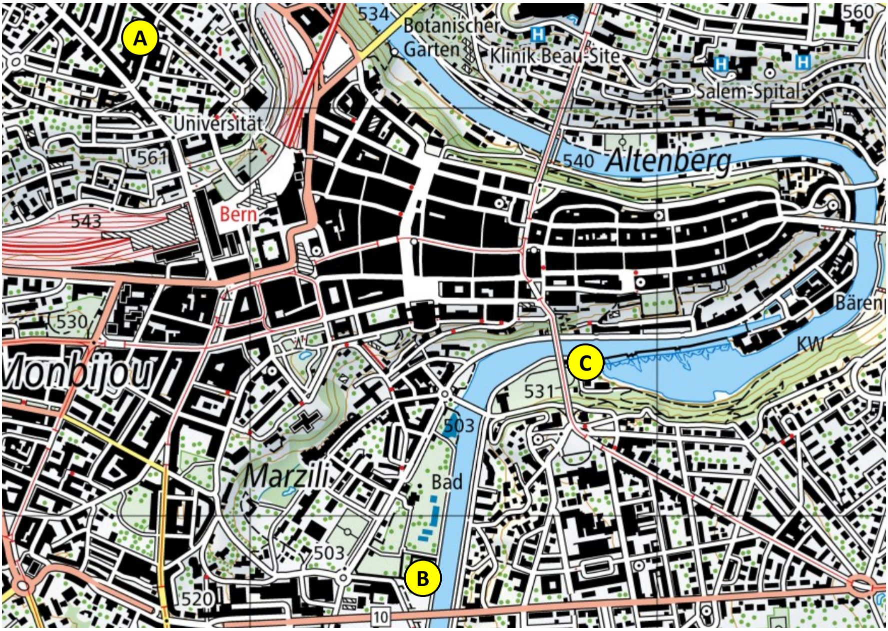
Location (Conference Venue)



A: Institute of Geography, Hallerstrasse 12, 3012 Bern

The conference venue is only a 7-minute walk from the train station.

Location (Conference Dinner and Ice Breaker)



A: Institute of Geography (Conference Venue),
Hallerstrasse 12, 3012 Bern

B: Dampfzentrale (Ice Breaker Reception),
Marzilistrasse 47, 3005 Bern

C: Restaurant Terrasse/Schwellenmätteli (Conference Dinner),
Dalmaziquai 11, 3005 Bern

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Cryosphere in polar regions

Chair: Stefan Wunderle

Global Cryosphere Watch – Status and Future Plans WMO – GCOS

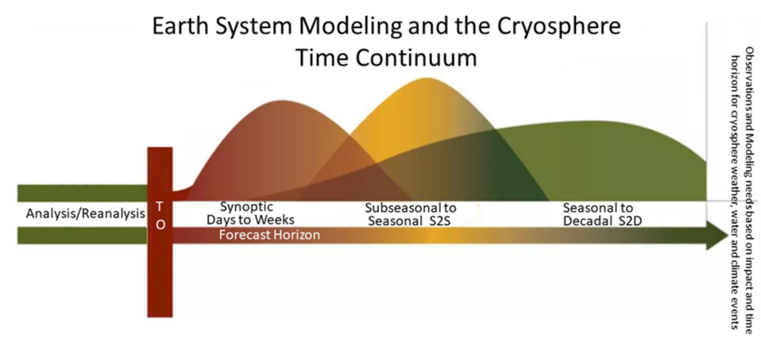
Rodica Nitu (rnitu@wmo.int)
Global Cryosphere Watch - WMO, Switzerland

The availability of, and access to cryosphere information is integral to the hydrometeorological, climate and environmental services coordinated through the programmes of the World Meteorological Organization (WMO), from global to regional and local levels and is critical for better serving the societal needs of the one hundred and ninety-three (193) WMO Members. The WMO goals of an Earth system approach to observations, modelling and prediction require additional actions on the integration and use of cryosphere information to close the gaps to a fully coupled cryosphere in the Earth system, as a mean to providing effective services responding to emerging needs, as is the access to effective warning systems.

The Global Cryosphere Watch (GCW) has been established by WMO to serve as a coordination mechanism, providing an active link between operational hydrometeorological services and the scientific communities to support the goals of the WMO Members.

The presentation will outline the current WMO priority activities where cryosphere is a critical element, covering different time scales, and the opportunities for engagement through GCW to support improvements to services with an effective integration of available cryosphere data and products.

The presentation will be an opportunity for advancing the dialogue of the role of WMO and will include, inter alia, the implementation of the WMO Unified Data Policy- paving the way working towards the free and unrestricted access to data, the role of GCW on the promulgation and dissemination of observing and reporting standards, the refocusing of the coordination of space-based capabilities for advancing benefits of, and access to space-based cryosphere observations, the key actions of the 2022 GCOS Implementation Plan, and the strengthening of the representation of cryosphere changes in the generation of information services.



MISR Arctic and Antarctic Sea Ice Albedo 2000-2022 Product Creation and Trend Analysis

Laura Aguilar (laura.aguilar.17@ucl.ac.uk), Jan-Peter Muller, Michel Tsamados, Thomas Johnson, Said Kharbouche
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Sea ice albedo is a key climate variable that affects the Earth's radiation budget. Spatio-temporal variation of sea ice albedo can be retrieved from pre existing satellite observation processing chains such as the CLARA2-SAL product. However, currently there is only one albedo product which is derived from instantaneous multi-angle measurements and that is from MISR [1]. The accuracy of surface albedo products is usually affected by error accumulation from atmospheric corrections to the top-of-atmosphere bi-directional reflectance factor (BRF) and the modelling of bottom of the atmosphere BRF and subsequent modelling to bi-directional reflectance distribution function (BRDF) using these BRFs. Sea ice surfaces being both anisotropic and dynamic have satellite product accuracies that also depend on the length of deployed time window, thus requiring sufficient numbers of observations over a short period of time.

In this study, we present a data fusion method using the high accuracy near simultaneous sampling of the Multiangle Imaging SpectroRadiometer (MISR) generated at the Langley Research Center applying a Rayleigh atmospheric correction, with the MOD35 cloud mask which is part of the MOD29 Surface Temperature and Ice Extent product derived from the Moderate Imaging Spetroradiometer (MODIS), both onboard the Terra satellite. We assume that the MISR bi-hemispherical reflectance (BHR) albedo is independent of solar angle, a crucial condition for instantaneous albedo products. As the accuracy of MOD29 cloud mask is assessed at >90% [1], this synergistic method can retrieve an improved BHR of the Arctic sea ice between April and September of each year from 2000 to 2022, and of the Antarctic sea ice between September and March of each year from 2000 to 2022. This study is a follow-on from Kharbouche and Muller (2018), that developed this method and focused on the Arctic region for the time span between March and September from 2000 to 2016. For both polar regions, we create four daily sea ice products consisting of different averaging time window (±1 day, ±3 days, ±7 days and ±15 days), each containing the number of samples, mean and standard deviation. For all four MISR cloud-free daily sea ice products, we derive 1km, 5km and 25km spatial resolutions. We perform an assessment of the day-of-year trend of sea ice BHR between 2000 and 2022 for the Arctic and the Antarctic, confirming a continuing decline of sea ice shortwave albedo in the Arctic depending on the day of year and length of observed time window, and providing a novel sea ice shortwave albedo product analysis for Antarctica.

Acknowledgements. This work was supported by the QA4ECV project www.QA4ECV.eu, of the European Union's Seventh Framework Programme (FP7/2007–2013) under grant agreement number 607405.

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Greenland Surface Runoff Extent, Mapped From Daily MODIS Imagery 2000 To 2021

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Streams and lakes develop each summer over the marginal regions of the Greenland ice sheet. These hydrological systems reach well into the accumulation area and indicate that surface runoff of meltwater is an important component of the mass balance of the Greenland ice sheet. Here we map daily slush limits, a proxy for the extent of surface runoff, using daily MODIS data (500 m spatial resolution). Our automated algorithm is applied to all of Greenland for the years 2000 to 2021. Albeit MODIS' spatial resolution is too coarse to resolve streams or lakes, the results highly agree to surface runoff mapping from higher resolution satellite imagery. The data document significant increasing trends in slush limits until the year 2012, but not thereafter. We compare MODIS mapped daily slush limits with runoff limits modeled by state-of-the-art regional climate models (RCMs). The comparison indicates that the RCMs overestimate runoff area, which is confirmed by auxiliary satellite and field data. Previously, validation of RCMs was limited to either very low or very high elevations on the ice sheet. Remotely sensed slush limits allow for systematic validation of RCMs at intermediate elevations. These new data can contribute to improved regional climate models and our estimates of Greenland's contribution to sea level rise.

Meltwater Retention Around the Greenland Ice Sheet Runoff Limit

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One mechanism of mass loss from the Greenland Ice Sheet is through surface melting and runoff to the ocean. At lower elevations of the ice sheet where bare ice is revealed in most summers, meltwater is abundant and the large majority of meltwater runs off via efficient river networks. At higher elevations of the ice sheet, melting becomes more intermittent, increasingly enabling net accumulation.

The elevation at which meltwater no longer runs off the ice sheet but is instead retained in-situ is termed the runoff limit. Thus, between the lower ablation area and the annual runoff limit there is a transition zone from 0 % meltwater retention, up to 100% retention by refreezing in the firn pore space.

Here we examine recent behaviour in meltwater retention around the runoff limit, with the ultimate aim of estimating the proportion of meltwater which is able to run off from this zone. We use passive microwave radiometry to identify the time at which the melt season ends each year, then we use Sentinel-1 synthetic aperture radar to investigate residual surface wetness in the autumn months which follow. We find that, in areas underlain by ice slabs, meltwater retention by refreezing can be widespread, especially if much of the previous winter's snowpack remains. Water takes several months to refreeze, remaining liquid beneath fresh snow cover. Conversely, in higher melt years where surface rivers are able to form which efficiently route meltwater downstream, then in-situ retention on top of ice slabs is much more limited.

Using field measurements of superimposed ice formation from the K-Transect, south-west Greenland, we are able to estimate total superimposed ice formation over our case study region. In conjunction with melt and surface hydrological catchment modelling we can calculate the proportion of meltwater which is retained in situ and thus derive the likely total runoff from around the heterogeneous runoff limit. This work will thus pave the way for improving parameterisations of retention vs. runoff in the surface mass balance models used to project the future mass losses of the Greenland Ice Sheet.

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Benchmarking Ice Mechanical Simulations at Supraglacial Lakes with Satellite and Airborne Remote Sensing

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Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Germany

Supraglacial lakes in Greenland drain eventually, e.g. by the opening of englacial channels. The mechanics of englacial channels is only poorly understood, including their potential to remain active over time. We discuss here one particular example for a supraglacial lake at 79°N Glacier, Greenland, that allows to draw some general conclusions. Viscoelastic simulations show that englacial channels will remain open at the glacier surface. Optical satellite imagery reveals that a gully that was the drainage pathway in 2020 was maintained, while moving with the glacier flow. Additional airborne data from 2021 is supporting this, too. In 2022 its size was nearly similar to 2020 and a subsequent drainage event has taken place through that same channel again. High resolution satellite imagery is used to detect the size of the channel over time, which allows to benchmark the simulation results and exemplifies the benefit of high resolution data for gaining process understanding.

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Snow cover
(basics and operational applications)

Chair: Kathrin Nägeli

EUMETSAT’s Interest in Snow Detection from Space

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EUMETSAT, Germany

In this presentation, the status of the operational and the future EUMETSAT‘s missions and EUMETSAT operated Copernicus missions, as pertaining to snow remote sensing will be given. As part of this presentation, the challenges and opportunities of operational snow products from EUMETSAT operated missions will be discussed, including the uptake of new technology, the refinement of existing algorithms, the potential of “synergy” products from multiple instruments and/or platforms, etc.

Retrieval of Subpixel Snow Albedo and Temperature from Visible through Thermal Infrared Sensing

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University of California, United States of America

The presentation reviews the state of the practice in solving for snow properties from spectroscopy and multispectral infrared—fractional snow cover, specific surface area of the grains, concentration and optical properties of light absorbing particles, liquid water content, snow water equivalent for shallow snowpacks, and snow temperature—accounting for effects of the atmosphere, terrain, vegetation, and soils on the signal measured by the CHIME (Europe) and SBG (U.S.) missions. CHIME will consist of imaging spectrometers in the 0.4-2.5 µm wavelengths on a pair of satellites. SBG will also include a similar spectrometer on SBG-Light along with a multispectral infrared instrument on SBG-Heat in the 4-12 µm wavelength range. The combination of satellites enables spectroscopic information at 8-day intervals and thermal day-night information at 3-day intervals. The inverse problem, using spaceborne remote sensing to retrieve the snow properties that govern albedo and temperature, addresses discontinuous snow, local and long-distance transport and deposition of light absorbing particles, forests and topography that shelter and obscure the snow, and consideration of surface roughness.

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Investigating the Snow Dynamics over Mountainous Terrains from EUMETSAT HSAF Snow Cover Product-H10

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The snow-covered area (SCA) is a key element of the hydrological cycle, and monitoring the SCA is crucial for understanding the snow dynamics. In order to map and realize the extent of snow cover at high altitudes, continuous monitoring is therefore necessary. Data from satellite remote sensing helps to capture land cover and changes in land cover. In this study the snow cover areas for the years 2011-2022 are retrieved from H10 binary snow cover product. H10 snow product, which is provided within the scope of the EUMETSAT H-SAF project for an extent of Pan Europe, is a daily operational product and it has a horizontal resolution of 0.05°. The anomalies in the snow covered days for January, February, March and April of 2022 are obtained by analyzing the long-term average values. In order to minimize the problems caused by the dense cloud cover, which is dominant in the Northern hemisphere, especially during winter, the 5-day moving window technique is implemented on the H10 product, and the number of cloud pixels in daily images is tried to be minimized by replacing them with snow pixels. Using the images obtained by this method, the average snow covered day data of each pixel is obtained between 2011-2022. The anomalies in the snow cover for January, February, March, and April 2022 in the study area are determined by subtracting the long-term average from the monthly average values and dividing the result by the standard deviation of the long-year average. The severe negative anomaly in the north part of Italy and positive anomaly in the east part of Turkey is discussed with respect to the anomalies in temperatures. Surface temperature anomalies for January, February, March and April 2022 are retrieved from ERA5-Land atmospheric reanalysis data, again by a similar methodology using the average temperature values obtained for the same time interval. The mean monthly discharge anomalies are obtained for three sub-basins having different mean altitude and basin area from Kizilirmak, Konya and Euphrates basins, which are the important basins having dams fed by snowmelt. The effect of snow cover day anomalies on mean monthly discharges is further discussed for these sub-basins.

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Evaluation of Snow Cover Properties in ERA5 with Several Satellite-based Datasets in Northern Hemisphere in Spring 1982-2018

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Seasonal snow cover of the Northern Hemisphere (NH) is a major factor in the global climate system. In the high latitudes, snow cover has a large influence on the surface energy budget and the hydrological cycle. Recent studies have shown that snow cover is changing, and snow cover in spring is especially sensitive to warming due to the strong surface albedo feedback. Observing snow cover at continental scale is only possible from satellites, but also reanalysis products provide estimates on variables related to snow cover which have been widely used in hydrological and climate research. The aim of this study is to analyze time series of surface albedo, snow water equivalent (SWE) and snow cover extent (SCE) in spring (March-May) in ERA5 reanalysis data and to compare the time series with several satellite-based datasets. For SWE reference data, we use SnowCCI v2 data for non-mountainous regions and the mean of Brown, MERRA-2 and Crocus v7 datasets for the mountainous regions. For surface albedo datasets, we use CLARA-A2 SAL product based on AVHRR data, and black-sky albedo product (MCD43D51) based on MODIS data. Additionally, we use Rutgers and JAXA JASMES snow cover extent products. Our study covers land areas north of 40 °N and the period between 1982 and 2018 (spring season from March to May). The preliminary results show that ERA5 tends to overestimate SWE and SCE in spring, whereas albedo is more consistent with the other datasets. The trends are mostly negative and consistent between the datasets, but spatial variability exists. We will further analyze the regional differences in trends and the discrepancies between the datasets. Results will also include analysis on the reasons behind the differenvces between the variables and the datasets.

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Poster Session I

Chair: Kathrin Nägeli

Impact of Assimilating ESA CCI Snow Cover on ECMWF Land Reanalysis

Kenta Ochi (Kenta.Ochi@ecmwf.int), Patricia de Rosnay, David Fairbairn
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It is important for climate reanalyses to ensure temporal consistency for long years. The land data assimilation system for ERA5 (the latest ECMWF reanalysis, Hersbach et al., 2020 https://doi.org/10.1002/qj.3803) relies on in situ SYNOP snow depth observations and the NOAA/NESDIS Interactive Multi-sensor Snow and Ice Mapping System (IMS) snow cover product. These observations play a crucial role to reduce systematic snow depth biases of the land model. However, the IMS snow cover product is assimilated in ERA5 from 2004 only. This results in a step-change in the ERA5 snow climatology in 2004, making the ERA5 snow irrelevant for multi-decadal snow cover trend analysis for example. In order to improve the temporal consistency in future reanalyses, the possibility of assimilating the ESA CCI Snow product have been investigated. The AVHRR CCI Snow cover product can be used from the early 1980's and opens possibilities covering longer years than IMS product. We conducted 3 different types of offline land reanalysis experiments: open loop (without snow data assimilation), IMS snow cover assimilation, and the AVHRR CCI Snow cover assimilation. The results show that the snow depth biases are reduced by assimilating the AVHRR CCI Snow cover, providing a reliable multi-decadal snow reanalysis. IMS and AVHRR snow cover assimilation provide consistent results for post-2004 periods, making it possible to ensure a reliable transition from AVHRR to IMS for real time production of the future reanalysis.

We will present the approach and the results of the ESA CCI Snow cover assimilation and discuss ongoing activities related to snow data assimilation in preparation of the future ECMWF reanalysis ERA6.

Towards a Consistent and Unified Land Data Assimilation Scheme by Analysing Multi-Layer Snow and Soil Temperature in the Operational Forecast System

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ECMWF, Germany

In numerical weather prediction (NWP), land surface analysis is providing the land surface state initial conditions for the operational forecast. In the framework of the Destination Earth initiative (DestinE) of the European Commission, the European Centre for Medium-Range Weather Forecasts (ECMWF) will use an enhanced version of its Integrated Forecast System (IFS) to produce the global continuous component of the Extremes Digital Twin, which aims at delivering improved capabilities for assessing and predicting environmental extremes. In ECMWF's IFS, near-surface diagnostic variables – such as 2-metre temperature and relative humidity derived by the forecast model – are assimilated to analyse the land control variables. Currently, control variables are analysed using several assimilation approaches – particularly a Simplified Extended Kalman Filter (SEKF) for soil moisture and a 1D Optimal Interpolation (1D-OI) for soil and snow temperature. The SEKF is the most advanced approach in the current IFS's land data assimilation system. The aim here is to explore whether producing more consistent land initial conditions by using the SEKF as a unified approach can provide more accurate initial conditions for the operational forecasts and the high-resolution simulations as part of DestinE's Extremes Digital Twin.

In this context, snow and soil temperatures will be analysed at multiple layers to achieve better representation of cold processes in the NWP at high spatial resolution. The SEKF involves an Ensemble of Data Assimilation (EDA)-based computation of the Jacobians between near-surface parameters and land variables. This work shows preliminary results of the sensitivities evaluated between 2-metre temperature and multi-layer soil and snow temperatures for different regions and synoptic times. With soil and snow profile information available in the analysis, melting characteristics and frozen soils can be considered more effectively, for example, to capture the evolution of permafrost and seasonal snow cover. A multi-layer snow and soil analysis allows better reflection of the heat transfer between land and atmosphere for more accurate estimation of depth-dependent temperature amplitudes that occur in diurnal to seasonal cycles. Future research will be on assessing whether enhanced land initial conditions can reduce systematic differences in the analysed land variables and impact on predictions of near-surface atmospheric parameters in operational forecasts.

Snow Cover Monitoring in the Cantabrian Mountains (NW Spain) from Webcam Images Network, Satellite Products and WRF Modelling

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Snow cover has a relevant influence on the climate, landscape, land-uses and socio-economic activities in the Cantabrian Mountains. Instead of that, few data about the snow cover exists in this area. Its study involves a certain complexity, due to the instability of the snow, rapid snow cover-melt processes, complex orography, climatic diversity and persistent cloudiness in some episodes.

The 2021-2022 snowfall episodes in the Cantabrian Mountains have been modelled using different configurations of the Weather Research and Forecasting (WRF) model and have been validated from satellite products and ground-based observations. For this purpose, the snow dynamics study is supported by a monitoring network composed of webcams along the study area. The installed webcams and snow poles allow the monitoring of snow cover and snow thickness for 105 sampling points. The Interactive Multisensor Snow and Ice Mapping System (IMS) product has been used to assess snow cover records over the whole Cantabrian Mountains. It has been used because of its ability to detect snow cover under cloudy conditions with a daily resolution of 1km.

The study of snowfall events 2021-2022 has resulted in a snow cover detection match rate of 84,3% between webcam images and WRF configurations and a match rate of 66,7% between webcam and the IMS product.

In conclusion, an important advantage of webcam snow monitoring is the improvement of the temporal resolution of the observations. It also enhances the continuity of the records, as they are not affected by the presence of cloud cover.

The validation of several WRF configurations versus ground-based observations has allowed to find the most suitable setting parameters for the Cantabrian Mountains. The combination of ground-based and satellite observations with numerical weather models will favour the study of the complex distribution and characteristics of the snow cover in this area, which is affected by the mountainous orography, relative mild climate and a variety of snowfall synoptic patterns.

New Development Of DLR's Global SnowPack- Integration Of New Sensors And Potential Applications Of The Near Real-Time Product

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The seasonal snow cover makes up by far the largest part of the cryosphere worldwide - if you look at the spatial extent. Therefore, the „Area covered by snow" is named as an essential climate variable (ECV) by the Global Climate Observing System (GCOS). The requirements of the variable are also defined here, namely the information should be provided daily and with a resolution of at least 1 km. To date, these requirements have only been met by medium-resolution optical sensors such as AVHRR, ATSR, MODIS or NPP VIIRS. These bear further limitations such as data gaps due to clouds or polar night. To overcome these limitations, DLR's Global SnowPack (GSP) was developed based on the daily MODIS snow product provided by the National Snow and Ice Data Center (NSIDC) to derive daily cloud-free snow-covered areas worldwide. This dataset exists since March 2000 and now covers a period of almost 23 years, enabling a statistical analysis of developments and trends in global snow cover dynamics. The evaluations are pixel-based or at catchment area level for hydrological questions. Since the latter require very time-sensitive information, a near real-time product was introduced. We will show the latest findings from the entire global time series analysis as well as possible applications for the newly developed near-real-time GSP product. In addition, due to the unknown remaining lifetime of the two MODIS sensors, the implementation of the sensor NPP VIIRS is presented to enable a seamless transition.

Improvement of Snow Data Assimilation for KIM

Sanghee Jun (appjsh@gmail.com), Kyung-Hee Seol, In-Hyuk Kwon, Myung-Seo Koo
Korea Institute of Atmospheric Prediction Systems, South Korea

As the lowest boundary of numerical weather prediction (NWP) models, land exchanges water and energy with atmosphere. Accurate land initial condition is essential to improve weather forecast skill. Especially, Snow, one of the important land surface variables, has high albedo and low thermal conductivity, and it can affect near surface temperature and water storage in NWP model. Thus, snow data assimilation was developed to correct stimulated snow of only deterministic system using snow cover observation for Korea Integrated Model (KIM) at Korea Meteorological Administration (KMA). KIAPS has a plan to improve this snow data assimilation, which has been running in an operation for KIM at KMA, shown in the following. First of all, we will use not only snow cover data from the interactive multi-sensor snow and ice mapping system but also actual snow depth data from in-situ observations. Secondly, realistic snow density will replace a constant value for calculating snow depth from snow water equivalent. Finally, we will initialize snow for the ensemble system to reduce the difference between deterministic and ensemble system.

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Satellite Altimetry as a New Data Source for Snow Depth Data Assimilation

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In mountainous terrain, snow amounts are largely unconstrained because of the absence of direct measurements, despite the high societal value of the water storage function. On a local scale, snow depth (SD) and snow water equivalent (SWE) are measured with stations, at single points, or with field campaigns that can be expensive and may not be feasible in remote areas. Currently used satellite-based methods to map SD or SWE are either expensive, like high-resolution photogrammetry; experimental, like the Sentinel-1 product C-snow; or have a poor resolution, like passive microwave.

Our aim is to exploit ICESat-2's ATLAS sensor: a satellite laser altimeter able to provide surface elevation measurements with an along-track resolution of 0.7 m and vertical accuracy better than 10 cm. Where an accurate snow-free digital elevation model (DEM) is available, it is possible to coregister it with snow-off ICESat-2 acquisitions. Hence, the difference between the ICESat-2 elevation measurements of the snow surface and the so-treated DEM directly translates into SD.

As a result, we obtain three pairs of SD profiles spread over a swath of 6.6 km for every clear-sky acquisition. However, this data is sparse in both time and space: the revisit time on a specific ground track is three months, and the spacing between adjacent ground tracks is 15 to 20 km in the mid-latitudes. For these reasons, a promising application of this resource is within data assimilation (DA) as a constraint for the snow-pack thickness, along with other forcing data. Most snow DA applications are constrained with snow cover, resulting in large model SWE and SD uncertainties. The recent Multiscale Snow DA System (MuSA) is open-source and enables joint assimilation with different variables by generating an ensemble of simulations through metereological forcing perturbation. The flexible snow model (FSM2) is incorporated, but we include a simpler degree-day model in the analysis. We assimilate the observations with particles and Kalman smoothers. An innovative feature in MuSA is the spatial propagation of the assimilated information through space. In this case, the propagation happens between pixels that lie close in a multi-dimensional space that includes aspect, elevation, and other terrain characteristics.

We show the first results from two case studies at different latitudes and with different morphology: the Izas catchment area in the Pyrenees, and the Hardangervidda area in the southern Scandes.

Artificial Intelligence for the Monitoring of Seasonal Supraglacial Lake Dynamics in Multi-Sensor Remote Sensing Data

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With accelerating climate change, the global ice sheets are exposed to increasing environmental pressure and ice mass loss. In Antarctica, the two main processes contributing to ice mass loss are oceanic and atmospheric forcing. While ocean forcing leads to the melting of ice shelves from below, atmospheric forcing drives the formation of meltwater ponds on the ice sheet and surrounding ice shelves. On the one hand, supraglacial meltwater lakes threaten ice shelf stability due to their potential to initiate hydrofracture and ice shelf collapse. On the other hand, supraglacial lakes can penetrate the entire ice sheet thickness and cause basal lubrication and sliding. Both processes lead to dramatic glacier acceleration and increased ice discharge thus contribute directly to ice mass loss and sea-level-rise. Furthermore, surface melting can be accelerated due to the comparatively low albedo of meltwater ponds. Even though recent progress in the monitoring of Antarctic supraglacial lakes contributed to an improved understanding of present-day Antarctic surface hydrology, detailed analyses of seasonal supraglacial lake dynamics and their impacts on ice dynamics are still missing, mainly due to the lack of an automated mapping method for supraglacial lake identification in optical and SAR satellite data.

Here, we present a framework for the monitoring of Antarctic supraglacial lakes in Sentinel-1 SAR and optical Sentinel-2 satellite imagery of the European Copernicus programme. In particular, state-of-the-art artificial intelligence and big data processing are exploited to enable the fully automated processing of large amounts of satellite data. For Sentinel-1, supraglacial lake identification was achieved through the training of a deep learning network based on residual UNet. For Sentinel-2, a pixel-based Random Forest classifier was trained on several spectral bands and indices. The full processing pipeline was then implemented as part the High-Performance-Computing (HPC) infrastructure at the German Aerospace Center (DLR) facilitating the automated processing and fusion of optical and SAR-based classifications. The functionality of the developed workflow is highlighted through its application on the full archive of available Sentinel-1/-2 satellite imagery over multiple Antarctic ice shelves. For the first time, the results reveal supraglacial lake dynamics at large-scale with strong intra-annual and inter-annual fluctuations in supraglacial lake coverage.

The Potential of Artificial Intelligence and Remote Sensing for Cryospheric Research

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Recent advances in artificial intelligence, especially in the field of deep learning, have allowed new insights into cryospheric systems. Nowadays, an abundance of satellite imagery, new developments in deep learning algorithms and easy accessibility to computational power enable new potentials for data processing and analysis. Here, we present a variety of deep learning applications for cold and polar regions providing new possibilities for observing and monitoring the cryosphere. The presented examples cover a wide range of applications such as mapping retrogressive thaw slumps in Arctic permafrost regions with high-resolution satellite imagery based on a UNet++ or the automated identification of the firn line in L-Band SAR data. Furthermore, methodologies for glacial lake mapping in the Himalayas with the GLNet and the detection of supraglacial lake dynamics in Antarctica based on optical and SAR satellite data will be introduced. Additionally, we address the automated extraction of calving fronts in Greenland and Antarctica providing new understandings of glacier and ice shelf front dynamics in an unprecedented spatial and temporal resolution. Taking together these new potentials of artificial intelligence for cold and polar regions, we welcome discussions on how these techniques can be applied to other areas in cryospheric science and what challenges and limitations this might involve.

Fractional Snow Cover Retrieval from Sentinel-3 Data Using Deep Convolutional Neural Networks

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Since 2012, deep learning has revolutionized the analysis of image data and is currently state-of-the art for solving a wide range of remote sensing image analysis tasks. We are now able to perform automated analysis of image data with much higher performances than ten years ago. Deep convolutional neural networks (CNN) consist of layers of convolutions that are applied directly to the input images and tailored to perform end-to-end analysis of the image data, e.g., pixelwise thematic mapping and parameter retrieval.

In this work, we propose to estimate the pixel fractional snow cover (FSC) from Sentinel-3 SLSTR data using a CNN called U-Net. As input to the U-Net, we use five Sentinel-3 bands as input (B1, B2, B3, B5 and B6). The network is trained to estimate the FSC (regression task) and for training the network, we apply a loss function that computes the mean squared error between the "ground-truth" (reference) FSC values and the output of the U-Net model. The reference FSC is generated from high-resolution Sentinel-2 MSI data which is then resampled to the match the low-resolution Sentinel-3 data. This yields a high accuracy reference dataset. .

Two experiments were carried out on a snow dataset comprising the four snow seasons of 2017-2020 in Scandinavia: One experiment testing the method's ability to generalize to the same geographical region, but to a new acquisition time/season. The other experiment testing the method's ability to generalize to a new geographical region. For the first experiment, we obtained a mean absolute error (MAE) of 4.3% using CNN, compared with 7.8% MAE for the standard algorithm of Salomonson and Appel. For the other experiment, we obtained a MAE of 3.6%, a similar level of performance, which also indicates that the network does not overfit to neither of the two setups.

The experiments and results show that the U-Net provide very good results for estimating FSC. We experienced that the performance is highly dependent of the quality of the training data, and the training data need to represent the variation of data values we will experience during inference. Hence, the training data need to include samples from different geographical locations, different times of the year, different snow conditions, and with a fairly balanced representation of FSC values.

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Public Webcams and its Potential for Complementing Satellite-Derived Snow Cover Information

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Snow cover is highly relevant for the Earth's climate system and its variability plays a key role in alpine ecology, hydrology, and socioeconomic systems. Snow cover information obtained by optical satellite remote sensing is an essential source to quantify snow cover variability from local to global scale. However, the temporal resolution of such measurements is often affected by persistent cloud coverage, limiting the application of high resolution snow cover mapping. Since 2011, the Remote Sensing Research Group at the University of Bern maintains an archive of freely accessible webcam images in Switzerland. The webcams are operated by restaurants, hotels, ski lift operators and private citizens and can be accessed by command-line tool wget and cron, a job scheduler on Unix-like operating systems. We illustrate how to georeference these images with as little as possible manual user input. Furthermore, we demonstrate the ability of webcam-based snow cover retrieval to complement satellite-based measurements.

The regional snow line elevation is a suitable indicator to describe snow cover distribution in mountainous regions and can be used, for example, as an input for hydrological modeling and gap-filling techniques for satellite-based snow cover retrieval. It is defined as the elevation that minimizes snow pixels below that elevation and snow-free pixels above that elevation. We derive the regional snow line elevation in an alpine catchment area using public webcams and compare our results to snow line information derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Sentinel-2 snow cover products. Moreover, we analyze the superior temporal resolution of webcam-based snow cover information and demonstrate its effectiveness in filling temporal gaps in satellite-based measurements caused by cloud cover.

Thermal Infrared Remote Sensing Across Scales to Monitor Surface Energy Fluxes over Rockglacier Murtèl, Switzerland

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Worldwide, the main alpine cryospheric components, such as snow, glaciers and permafrost, undergo drastic changes due to global climate change. The alpine cryosphere is particularly vulnerable and affected. The surface energy budget is out of balance and requires an improved monitoring, for rugged terrain in particular at the spatial length scale. It is crucial to be able to capture the individual heat fluxes and understand their spatial variability and interactions at the complex surface-atmosphere interface. Particularly key is an improved representation of all energy and mass fluxes that determine the ground thermal regime for high mountain permafrost in the first place. However, spatial monitoring of surface energy fluxes is challenging and requires imaging systems.

This research is embedded in the international science consortium of the upcoming TRISHNA (Thermal infraRed Imaging Satellite for High-resolution Natural resource Assessment) mission, a high-resolution space-time thermal infrared (TIR) mission aimed to enhance our understanding of the water cycle and improve our management of the planet's water resources by the indo-french space agencies. The Trishna T-SEC project aims to contribute towards the key TRISHNA scientific objectives, and focuses on using TIR remote sensing to understand and measure the water status and stress of continental ecosystems over mountainous and tundra regions.

Here, we present multi-sensor TIR data to obtain spatially distributed land surface temperature (LST) information of Murtèl rockglacier in the Engadin. Besides two years of data from a terrestrial TIR camera, we obtained drone data, airborne data and point-scale radiometer and radation observations. We put a specific focus on the importance of individual processing steps for validation and calibration to obtain accurate LST data.

Our study works towards an enhanced application of thermal infrared remote sensing techniques in rugged and complex terrain, but also fosters an advancement in energy budget assessments of cryospheric components at varying spatial length scales.

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Snow Hydrology – Snow Water Equivalent

Chair: Zuhal Akyurek

Efforts to Improve the Northern Hemisphere Snow Water Equivalent Retrievals in the ESA CCI+ Snow Project

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Reliable information on snow cover across the Northern Hemisphere and Arctic and sub-Arctic regions is needed for climate monitoring. Warming surface temperatures during the recent decades have driven a substantial reduction in the extent and duration of Northern Hemisphere snow cover. These changes in snow cover affect Earth's climate system via the surface energy budget and influence freshwater resources across a large proportion of the Northern Hemisphere. In contrast to snow extent, reliable quantitative knowledge on seasonal snow mass and its trend were lacking until recently.

FMI has been working with ECCC on retrieval of terrestrial snow mass using passive microwave radiometers in several ESA projects, such as GlobSnow and Snow CCI. The ESA Snow CCI project initiated in 2018 strives to further improve the retrieval methodologies for snow water equivalent (SWE) from satellite data and construct long term climate data records (CDRs) of terrestrial snow cover for climate research purposes.

The efforts to improve satellite-based retrieval of snow water equivalent has resulted in an enhanced resolution SWE record spanning 1979-2021, with 12.5km spatial resolution (Luojus et al. 2021). The retrieval applies the GlobSnow approach which combines satellite-based data with ground-based snow depth observations. Further, the team has applied a bias-correction approach to improve the reliability of the long-term climate data records of terrestrial snow mass, presented in Pulliainen et al. 2020. The approach is being further improved in ESA Snow CCI project.

The new SWE data record and upcoming Snow CCI datasets will improve our estimates of the satellite-era snow mass changes and trends for the Northern Hemisphere.

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Integrating Snow Mass Estimates for Mountain Areas in the Snow CCI+ SWE Product

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Accurate characterization of seasonal mountain snow is critical to understanding the mountain hydrologic cycle. The European Space Agency Climate Change Initiative Snow Water Equivalent Climate Data Record (ESA CCI+ SWE CDR), which combines passive microwave observations with in situ snow depth measurements to estimate SWE, does not provide data over complex terrain. There are valid and well-understood reasons for this exclusion, but it means that alternative approaches are needed to fill in gaps in mountain areas. Here, we explore using a Bayesian ensemble-based data assimilation approach for this need. It exploits the relationship between SWE and the depletion signal in remotely-sensed fractional snow cover observations when combined in a Bayesian data assimilation framework. Previous applications of this method over the Western US and High Mountain Asia (Liu et al. 2021) assimilated optical fractional snow cover area (fSCA) estimates derived from Landsat and/or MODIS imagery. We explore whether the ESA CCI+ Snow Cover Fraction (SCF) CDR, which provides global coverage and pixel-wise uncertainties, can replace the Landsat and MODIS data. Our long-term objective is to develop continental (and eventually global/hemispheric) mountain SWE estimates that can be merged with the existing Snow CCI+ SWE dataset to produce a gap-free SWE product informed by remote sensing.

We first evaluate an implementation of the Snow CCI+ SCF CDR (0.01° spatial resolution) over a test region in the Tuolumne River basin, California. We use the viewable SCF (SCFV), which is an estimate of the snow viewable on top of the forest canopy. Its performance is compared to that obtained from a baseline dataset that uses Landsat fSCA observations, to estimate posterior SWE and both sets of output are compared to in situ SWE estimates from snow pillows and the Airborne Snow Observatory (ASO). When resampled to conform to the original assimilation framework resolution (480m), the CCI+ SCFV posterior SWE had larger errors than those obtained when using the baseline Landsat product. In contrast, aggregating the assimilation framework to the native CCI+ resolution (0.01°) produced posterior SWE that compared well to the baseline product. However, we still see weaker performance during the ablation period and in a dry year (e.g. 2015) because Snow CCI+ SCF retrievals (and hence posterior SWE estimates) are biased low compared to the Landsat fSCA. We also note improved performance by relaxing the Snow CCI+ SCFV uncertainty from its supplied average value of 8% to 15%. We will expand these initial tests to other watersheds in the western US where ASO data are available, and explore the feasibility of implementation over western Canada. We place particular emphasis on adapting the CCI+ SCF uncertainty values to allow temporally and spatially dynamic uncertainty estimates within the assimilation scheme.

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On the Use of High-Resolution Remote Sensing Product to Generate SWE Maps

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Snow Water Equivalent (SWE) represents the water stored in the snowpack and is the most important variable from a hydrological point of view. Thanks to the recent launch of the Sentinel missions in the framework of the Copernicus program, it is possible to monitor the snow evolution with better spatial and temporal resolution. This represents an advantage when dealing with the snow accumulation and melting dynamics that are driven by complex topography. In detail, temporally sparse acquisitions from Sentinel-2 or Landsat missions combined with daily acquired low-resolution acquisitions e.g., from MODIS allow the monitor of the snow cover area (SCA) evolution (Premier et al., 2021). The availability of several years of these acquisitions is useful to carry on historical analyses on the snow patterns that repeat within a catchment due to the topography and meteorology of the study area. On the other hand, the Synthetic Aperture Radar (SAR) mounted on board of the Sentinel-1 missions has shown to be of great interest for monitoring the snowpack melting phases (Marin et al., 2020). We investigate how the combination of all this information together with a parsimonious use of in-situ measurements and eventually a simple model to estimate the potential melting (e.g., a degree day model) allows to reconstruct SWE reanalysis time-series for the last 10 years. Moreover, in this work we aim exploiting the snow depletion curves (SDC) to predict in near real time the total SWE of a given catchment. When evaluated against a reference product (i.e., Airborne Snow Observatory), the method shows a bias of-40 mm and a RMSE of 216 mm for a catchment of 970 km2 in Sierra Nevada (CA).

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Assessing the Potential Interferometric and Polarimetric SAR Data for the Retrieval of Snow Water Equivalent

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The Snow Water Equivalent (SWE) describes the amount of water contained within a snowpack. It can be used in hydrological and climate models, as well as for the planning of water resources. In-situ measurements provide precise information, but they can be only performed on a limited number of locations and are challenging to obtain in remote areas.

For monitoring large areas with high temporal resolution, remote sensing is a powerful mapping tool. Particularly Synthetic Aperture Radar (SAR) can be utilized for cryosphere applications, as is it independent from illumination and weather conditions. Depending on the frequency, radar waves can penetrate into dry snow, where they are refracted, affecting path length of the wave. In [1] a model was proposed, which was extended in [2], where the Differential Interferometric SAR (DInSAR) phase of SAR two measurements can be related to the SWE change between them. However, the method is limited because the phase lies in the interval [-π, π]. This leads to a phase wrap of the interferometric phase, when the SWE change is higher than a certain threshold, which depends on the frequency.

In order to mitigate and estimate the amount of phase wraps, SAR polarimetry can be used. The Co-polar Phase Difference (CPD) can be calculated between the VV and HH polarized channel which has a correlation to the fresh snow depth. With a model from [3], the CPD can be inverted to the fresh snow depth.

This study investigates the potential of including polarimetric variables into the DInSAR SWE retrieval algorithm in order to obtain a more accurate SWE estimation. For that purpose, airborne and spaceborne SAR data sets are used. First results show, that polarimetry contains information on the snow depth and can therefore be used to estimate the amount of phase wraps in the DInSAR phase. By correcting these in the retrieval algorithm, a higher accuracy between the estimations and ground measurements is achieved.

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Snow from space: combined analysis of Snow Water Equivalent from Cosmic Ray Neutron Sensors and Fractional Snow Cover products from Sentinel and MODIS

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Snow Water Equivalent (SWE) is listed under the Global Climate Observing System (GCOS) as a product of the Essential Climate Variable (ECV) 'snow', making it a valuable parameter for snow monitoring. However, SWE cannot be directly measured by satellite-based sensors. Conventional ground-based measurements are performed at point scale, which usually introduce a bias since heterogeneous terrain causes uncertainty in the distribution of snow height and density patterns. A promising new technique is above-snow Cosmic Ray Neutron Sensing (CRNS). The method is sensitive to SWE within approximately 200 m around the station, providing an average that is more reliable in heterogeneous terrain. Furthermore, this large footprint makes it well suited for a comparison with satellite remote sensing products. The measurement principle of CRNS is based on the interaction of secondary cosmic rays with hydrogen atoms, leading to the creation of fast neutrons that are detected by the sensor. The neutron count rate is a proxy for the abundance of ambient water, which makes CRNS not only sensitive to SWE, but also to other water sources, such as soil moisture and biomass. Derived multispectral satellite remote sensing products, like Fractional Snow Cover (FSC), provide valuable information on the temporal presence of hydrogen pools that cause a trend or offset in the CRNS signal. In this study we compare the neutron count signal of 65 CRNS stations within the COSMOS-Europe network with FSC products derived from Sentinel-2 and MODIS (Moderate-resolution Imaging Spectroradiometer). We classify the daily CRNS neutron counts by presence and absence of snow, and aim at identifying typical signal properties of lowland, pre-alpine and alpine research sites. By analysing the typical ranges of neutron counts, we investigate how well stations at different altitudes are suited for the application of CRNS-SWE measurements. The analysis has been assisted by FSC products to indicate snow events and melting episodes, and by CORINE Land Cover data of Copernicus to quantify additional hydrogen sources. We found that the range of CRNS signal offset follows an altitudinal trend. While high soil moisture and the presence of vegetation result in an increased snow-free signal offset, fresh snowfall is indicated by an abrupt drop in the CRNS signal. The comparison of the two remote sensing FSC products shows that the FSC derived from MODIS is mostly lower than the FSC from Sentinel-2. Given the results, CRNS is a powerful tool for SWE measurements at alpine sites, where terrain heterogeneity is high, but the abundance of no-snow hydrogen sources is low.

Comparison of Passive Microwave Dry Snow Detection Algorithms and Application to SWE Retrieval

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Terrestrial snow cover is a key component of the Earth's climate and hydrologic system. To quantify the impacts of snow cover, reliable monitoring of seasonal changes in snow mass is required, which is accomplished through snow water equivalent (SWE) retrieval from passive microwave satellite data. SWE retrieval methodologies, such as GlobSnow (Luojus et al., 2021), typically implement passive microwave dry snow detection as one of the main processing steps to restrict the actual SWE retrieval to snow-covered areas.

Accurate dry snow detection is crucial for this application, however algorithms tend to underestimate snow extent. As part of the GlobSnow SWE product development, a long-term assessment of six current dry snow detection algorithms is carried out to determine their capabilities on hemispheric scale with respect to exhaustive in situ data and NOAA IMS snow maps (Zschenderlein et al., under review).

We show that the decision tree by Grody and Basist (1996) achieves the best detection accuracy and spatial performance, followed closely by the algorithm of the EUMETSAT H SAF snow status product (Pulliainen et al., 2010) which implements Hall et al. (2002) with empirically updated brightness temperature thresholds. In both cases, we find that the underestimation of snow extent by conventional daily snow masks can be significantly reduced through cumulative snow masks, which retain snow pixels once detected for the rest of the season.

GlobSnow currently implements the cumulative version of Hall et al. (2002) with its original thresholds. By using either of the two best dry snow detection algorithms instead, the validation for hemispheric SWE retrieval in the GlobSnow framework shows a noticeable improvement of the current statistics—reducing the bias by up to 0.71 mm and the RMSE by up to 1.0 mm.

This highlights the impact of dry snow detection on the quality of SWE retrieval and therefore on long-term climate data records, and encourages further optimisation of dry snow detection algorithms.

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Microwave technologies to observe the Cryosphere

Chair: Stefan Wunderle

Measuring Coherent Polarimetric Backscatter Time-Series Covering 1-40 GHz with the ESA WBSCAT Scatterometer

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Development and validation of microwave scattering models for snowpack and vegetation strongly benefit from the availability of dense temporal time-series of accurate in-situ radar backscatter measurements. The WBSCAT scatterometer is a scatterometer developed for ESA by Gamma Remote Sensing AG covering the frequency range from 1-40 GHz and is capable of making coherent polarimetric measurements of radar backscatter. As part of the ESA Snowlab (2018-2019) and Snowlab-NG (2019-2020) projects, WBSCAT measured fully polarimetric radar backscatter multiple times each day at Davos-Laret, located at an altitude of 1514 meters a.s.l. The instrument was mounted on a static tower, 8 meters above the ground surface. Scatterometer measurements encompassed a range of different incidence and azimuth angles and are part of a comprehensive data set including radiometric microwave emission, air and snow surface temperatures, precipitation, and snowpack characteristics e.g., height, moisture content, snow water equivalent (SWE), density, and structure. WBSCAT was mounted on a 2.5-meter rail, inclined 45 degrees from horizontal, that permitted calculation of tomographic profiles showing formation of different scattering layers in the snowpack for different frequency bands. The scatterometer instrument is based on a vector network analyzer (VNA) using internal standards to calibrate the VNA and then used for calibration of internal amplifiers and switches. Antenna gain patterns were measured at the ESTEC HERTZ anechoic chamber to permit calculation of the effective illuminated scattering area. The instrument worked reliably during these observation seasons and have successfully produced time-series of the radar scattering coefficient σ_0 and interferometric phase and coherence.

Radar Observations of Coherent Backscatter Enhancement for Snow Parameter Estimation

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The Coherent Backscatter Opposition Effect (CBOE) is a phenomenon that causes an increase of backscatter intensity of coherent radiation by up to a factor of 2 in the direct return direction, due to constructive interference of time-reversed pairs of scattering paths. It only occurs in particular types of low-absorbing, disordered media (including snow at radio frequencies), and has a characteristic narrow angular peak centered on the direct return direction with a usual angular width of less than 1 degree. The full characterization of the effect requires bistatic scatter measurements, i.e. measurements where the transmitter and the receiver can be spatially separated. Once characterized, the properties of the peak can be linked to properties of the scattering medium (Hapke, 2012). The effect has been known in the optics and planetary science fields for several decades, and was considered in a few terrestrial snow scattering models (Tan et al., 2015), however it has so far lacked a full, bistatic characterization within the Earth's cryosphere at radio frequencies.

We present the results of the first characterization of this effect in the Earth's snow cover using bistatic radar instruments (Stefko et al., 2022). With the ground-based system KAPRI we confirmed the presence of the effect at Ku-band in seasonal snow on top of the peak Rinerhorn in Davos, Switzerland. Furthermore, using the spaceborne constellation TanDEM-X, we detected the effect at X-band in deep firn in the Jungfraufirn area of the Great Aletsch Glacier. For both of these measurements, we were able to quantify the angular shape of the enhancement peak. From the angular shape, in turn, we estimate the scattering and absorption properties of the medium. This was achieved using a CBOE scattering model which links the shape of the intensity enhancement peak to the scattering and absorption mean free paths within the medium.

These results thus showcase the ability to quantify scattering and absorbtion lengths within snow cover by radar observations of the CBOE. This, in turn, could potentially lead to quantitative characterizations of variables such as snow depth or snow cover extent (Stefko et al., 2022). Furthermore, the TanDEM-X results demonstrate the possibility of global-scale observations, using spaceborne bistatic radar sensors. We will discuss how global observations of this effect could complement other remote sensing methods and improve the accuracy of methods such as model-based parameter inversion or estimation of penetration bias for radar interferometry, thus leading to better understanding of snow as an essential climate variable.

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Time Series Of Vertical Snow Profiles Measured By SAR Tomographic Profiling - A Comparison With Reference Snow Characterizations

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Seasonal snow in alpine regions at altitudes around 1500m above sea level is subject to strongly varying meteorological conditions, often with diurnal cycles of temperatures around the freezing point, and precipitation in the form of snow and rain. These varying conditions lead to pronounced vertical gradients of snow temperature that interchange with almost constant snow temperature profiles that drive the metamorphosis of the snow pack.

During the ESA Snowlab project, time series of tomographic profiles have been measured over several snow seasons with the ESA SnowScat (9.2 - 17.8 GHz) and the ESA Wideband Scatterometer (WBScat) (1 - 40 GHz) at the SLF snow test site in Davos-Laret, Switzerland, located at about 1500m above sea level.

The microwave instruments were mounted on a tower, movable on a tilted rail to allow aperture synthesis for tomographic profiling.

In this contribution, we present an extensive comparison of the time series of radar tomographic profiles of the snow pack at different frequency bands (including 1-6GHz, 12-18 GHz and 28-40 GHz) with time series of reference snow characterizations obtained nearby by means of snow pit and SnowMicroPen (SMP) measurements and further auxiliary environmental parameters.

The detailed analysis of the three bands of the WBScat tomograms provides insight into relative change of location and strength of backscatter within the snowpack (e.g. during melting and refreezing cycles) as a function of various parameters (snow surface temperature, liquid water content).

We also compare the vertical distribution of backscatter versus total backscatter. Clearly, for 9.2-18 GHz and higher frequencies the tomographic profiles show substantial scattering from within the snowpack, depending on the snow conditions. The ground contribution is often not the strongest contribution.

The three bands measured with WBScat show evidence of frequency-dependent (in some cases opposite (1-6 GHz)) backscatter trends in the time series. The results indicate that, except at the frequency band 1-6GHz, substantial backscatter is contributed by horizontal layers (e.g. melt-freeze crusts) and potentially also by vertical structures that develop during the snow metamorphosis. Our analysis includes a detailed comparison of the tomographic profiles with accompanying SMP force and SWE/snow density and SSA parameters.

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The Airborne Cryosphere-Observing SAR System (CryoSAR): Season-long Airborne and Ground-based Observations of Terrestrial Snow and Lake Ice During Fall 2022 and Winter 2023

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The Cryosphere-Observing SAR (CryoSAR) system is a Ku- and L-band polarimetric synthetic aperture radar (SAR) system designed to conduct observations of snow and ice on land and over water bodies, and soil moisture status. The CryoSAR system is a fully polarimetric SAR with the capability to conduct single or repeat pass observations for interferometric SAR (InSAR) applications. There is significant interest in the Ku (13.5 GHz) polarimetric response and L-band (1.3 GHz) InSAR measurements of snow on land and water as tools to estimate snow water equivalent, a key variable in water resource management applications and in climate change studies. The CryoSAR radars can be operated independently or together. They can also be deployed on a relatively small aircraft, such as a Cessna 208, which is widely available across North America, Europe and beyond, making the system relatively agile in its deployment. An adjustable mounting system has been designed to enable the instrument to be installed from inside and aircraft and at specified look angles. In fall 2022 and winter 2023, a season-long deployment of the system was conducted in Ontario as part of a Canadian Space Agency-funded project and in support of the Terrestrial Snow Mass Mission. Flights were conducted over selected sites in Ontario including the Haliburton Highlands and Powassan. Field campaigns were also conducted on the ground to provide correlative ground reference data. A combination of traditional field observations of snow properties, and detailed state-of-the-art measurements of microstructure properties were made to quantify the snowpack bulk and stratigraphic characteristics of the snow at the different field sites. This presentation discusses the first observations made with the CryoSAR system at Ku- and L-band. Results focus on the polarimetric responses from snow on land and on lake ice and demonstrate its applicability for terrestrial snow monitoring.

A Field Campaign on InSAR Retrieval of Snow Mass in Alpine Terrain

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The lack of regular, area-wide observations of snow water equivalent (SWE) is a main gap in monitoring of the global cryosphere. Repeat-pass differential SAR interferometry (RP-InSAR) offers a well-defined physically based approach for mapping SWE at high spatial resolution by measuring the path delay of the radar signal propagating through a dry snowpack. A critical issue for routine application of RP-InSAR is the temporal decorrelation caused by changes in the complex backscatter signal. In C-band comparatively moderate snowfall amounts may already cause complete decorrelation whereas this effect is of less concern in L-band. The use of L-band RP-InSAR for SWE mapping has by now been limited to case studies because of the lack of regular repeat observations over snow-covered land surfaces. In anticipation of the enhanced repeat observation capabilities of upcoming L-band SAR systems, such as ROSE-L, we conducted field campaigns in two Alpine test sites to consolidate the RP-InSAR retrieval tools and evaluate the product performance. The use of C-band RP-InSAR for SWE retrievals was as well studied. Among the topics addressed are the effects of snowfall intensity on temporal decorrelation, the impacts of topography and land cover type on the RP-InSAR phase and resulting SWE, and possible effects of snow structural properties on the observed signal.

During March 2021 an experimental airborne campaign was carried out in the high Alpine test site Wörgetal/Kühtai near Innsbruck, addressing two complementary approaches for SWE measurements: (i) exploring the measurement concept of a geostationary C-band SAR mission for retrieval of dense SWE time series; (ii) consolidating the assessment of the RP-InSAR based SWE retrieval method and performance in support of mission preparation for ROSE-L and Sentinel-1 NG. The activities were performed by DLR and ENVEO within the ESA project SARSimHT-NG. Within the period 2nd to 19th March 2021 multiple C- and L-Band SAR data were acquired F-SAR flights on 7 days spanning two snow fall events of about 10 cm and 40 cm mean fresh snow depth. On days of the F-SAR overflights vertical profiles of physical snow parameters were measured in snow pits at different locations as well as snow depths along transects. In the presentation we report on the impact of snowfall and other environmental parameters on C- band and L-band InSAR coherence over time periods ranging from several hours to days, and report on the performance of the InSAR SWE retrievals performed over the test sites Wörgetal/Kühtai. The campaign activities and the presented results are of relevance for preparing snow monitoring activities with current and upcoming L-Band SAR missions including SAOCOM A/B, NISAR and ROSE-L. Furthermore, the investigations are of relevance for exploring the combined use of C- and L-Band SAR data for monitoring main snowpack parameters.

Intertwined Essential Climate Variables: Permafrost and Snow

Chair: Gabriele Schwaizer

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Arctic Permafrost: The importance of snow

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From the soil pore space to continental spatial scales, permafrost in the Arctic is undergoing warming and degradation. Small-scale changes can be observed, such as shifts in freezing and thawing cycles, hydrology and precipitation, that have substantial global-scale effects. Yet, forecasting how observed drivers of permafrost thaw cascade their effects to other spatial and temporal scales is challenging. Shifts in winter air temperatures are mitigated by the snowpack in a complex fashion, as snowpack thickness, snow thermal properties evolve. Complex phenomena such as depth hoar formation, refreezing of melt water and wind compaction change how the soil cools in winter. At the smallest scale, the complex microstructure and spatial distribution of both the snowpack and ground ice determine their thermal properties and affect the permafrost.

We report on the complexity of the snowpack and how its inter-annual variability influences the permafrost ground thermal regime. Specifically, we present observational data on automated snow water equivalent / snow density measurements from two Arctic Sites located in Spitsbergen (Bayelva) and Siberia (Samoylov). In addition, we present a novel framework for automated classification of snow cover from time lapse images. For both sites, the complexity of the snowpack and its inter-annual variability influence the ground thermal regime. Tying observations of changes at the small to regional scale to the consequences of global warming, there may be surprises in terms of permafrost response, due to possible non-linear changes as well as lag effects.

The Integrated Description of the Snow Cover in Polar Areas: a Multi-scale and Multi-platform Solution

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The description of the snow cover dynamics represents a critical task, where the gap between ground-based measurements and spaceborne observations that must be approached. The presented strategy is based on integrating different spatial scales and on combining several data sources. Automated systems are the key solutions selected for describing the spatial distribution of the snow cover during time as well as the optical behaviour of the seasonal snow on the ground. One component of the proposed approach is terrestrial photography, which is focused on assessing the fractional snow-covered area. Specific algorithms are available for processing large image datasets and for projecting snow-classified pixels on the surface. On the other hand, spectral reflectance has been assessed using narrow-band and hyperspectral systems in the visible, near and short-wave infrared wavelength domains. Finally, this integrated strategy has been implemented in the pilot site located in the Svalbard Archipelago (Ny-Alesund, north-western Spitsbergen). The produced knowledge represents an useful dataset for calibrating and validating remotely sensed data. Automated systems are, in fact, valuable assets useful for continuously provide information about the state of the snow cover, limited in terms of spatial extension (10 m2 up to 10 km2), but almost independent from meteorological conditions and characterized by high time-resolution. The availability of time-lapse cameras, potentially operating for a long time (the longest times series covers about 20 years), offers therefore the opportunity to have a continuous ground-truth for validating remotely-sensed data. Looking for an upscaling strategy from in-situ observations to satellite data, terrestrial photography can be easily linked to satellite sensors characterized by higher spatial resolution (Sentinel-2, Landsat 8, etc...). Similarly, the availability of optical devices, namely albedometers, supports the description of the spectral behaviour of the snow cover. The combination between in-situ and satellite radiometric data is the straightforward approach for assessing the evolution of different snow cover types during the melting season.

Unraveling Fire Permafrost Interactions in Northeastern Siberian Tundra Using InSAR and Machine Learning

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Permafrost soils in boreal forests and tundra store more than two atmospheres worth of carbon, yet the vigorous permafrost-carbon-climate feedback loop remains poorly understood. In addition to ongoing strong warming, fires can further accelerate permafrost degradation and trigger the release of ancient carbon into the atmosphere. Despite the urgency after the recent Arctic fire records of 2019, 2020 and 2021, fire-permafrost interactions are currently not included in Earth system models from the sixth assessment of the Intergovernmental Panel on Climate Change (IPCC). This is because large-scale observations of fire-induced permafrost degradation are lacking. Therefore, we studied fire-induced permafrost degradation using the Interferometric Synthetic Aperture Radar (InSAR) technique and time series of Sentinel-1 (S-1) imagery. In this pilot study, we tested our approach on fires from 2019 and 2020 in the Chokurdakh area, Northeastern Siberia. We processed time series S-1 SAR data from the snow-free season (June-October) where S-1 SAR image selection was automated by using the MODIS snow cover products. To understand the drivers of InSAR-derived subsidence, we applied the XGBoost regression algorithm using subsidence as a response variable and ten other environmental variables as predictor variables. First, we found that the time series InSAR technique is suitable for deriving subsidence over fire-affected permafrost terrain. Second, the fire-affected permafrost terrain experienced exacerbated subsidence compared to the surrounding unburned area. Third, the XGBoost regression model revealed land surface temperature (LST) and albedo as the primary predictor variables accounting for more than 50% of the predictive power. From this pilot study, we conclude that the InSAR technique has the potential to study fire-permafrost interaction at the northern circumpolar scale. The permafrost degradation in many tundra areas is likely dominated by fire-induced changes in the surface energy balance. Models can use our data to parameterize subsidence and thermokarst processes associated with permafrost degradation due to fire.

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Modeling Permafrost Distribution Using Machine Learning Models In Khumbu Region, Nepal

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Rock glaciers are an important indicator of the existence of permafrost. Study of permafrost variation is necessary to understand the stability, its nature in regards to global warming and hydrology. A rock glacier inventory of Khumbu region was prepared at an elevation 4000-5600 meter; classified based on their activity (Intact/Relict) from Google Earth. Three statistical machine learning models with topo-climatic input as predictor variables used to generate permafrost probability distribution maps in the Khumbu region of Nepal at 30 meter resolution. Predictor variables were Slope, Aspect, Elevation, Mean Air Temperature and Potential Incoming Solar Radiation. All models show similar performance, with Logistic Regression having 0.73, Random Forest at 0.7 and Support Vector Machines at 0.727. Further analysis shows the model sensitivity to randomness from (i) Data Partition, (ii) the nature of the models. Thus results are variable and accuracy and AUC-ROC, and thus selecting a cutoff probability to indicate permafrost gets complicated. Furthermore, the Random Forest model still guesses when the models are allowed to be uncertain about the prediction around a range of increasing cutoff brackets. Thus, a simple model like Logistic Regression is preferable for its flexibility in Solukhumbu region and its interpretability.

ESA CCI+ Snow / SnowPEx+

Chair: Julia Boike

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Recent Developments Towards The Upcoming Snow Cover Fraction Climate Research Data Package V3.0 From Terra MODIS And Sentinel-3 SLSTR Data Within ESA CCI+ Snow

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Seasonal snow cover is the largest cryospheric component on land areas during the Northern Hemispheric winter season. The impact of snow cover on different short-term processes on the Earth's system due to its high temporal and spatial variability, and in a long-term view on the global climate system is evident. Optical satellite data have been widely used in the past decades to get information on snow covered areas. But the products were limited by the spatial, temporal, and radiometric characteristics of the satellite sensor or by the capabilities of the algorithms, many of which only provide binary snow classification or, in forested areas, only snow viewable from above. Within ESA CCI+ Snow, a method has been established to estimate fractional snow cover maps, and to provide for forested areas consistent information on the snow cover fraction viewable on the top of the forest canopy (SCFV) and the snow cover fraction on the ground (SCFG) underneath forest canopy. The processing chain for each satellite granule consists of four main modules: 1) preprocessing of satellite data, 2) cloud screening, 3) pre-classification of certainly snow free areas, and 4) snow cover fraction estimation for SCFV and SCFG and associated uncertainty estimation. Daily global maps are generated by merging all SCFG and SCFV granules per day, respectively, as well as the associated uncertainty estimation. Time series of daily global fractional snow cover maps, SCFV and SCFG, with about 1 km pixel spacing including the associated uncertainty per pixel have been generated from daily Terra MODIS data acquired between 2000 and 2020 and released as Climate Research Data Package (CRDP) v2.0 in November 2021. After the validation and the assessment of the SCFG and SCFV products from MODIS data in climatological and hydrological models, the following main development steps have been identified to further improve the products for the next version: 1) adjust the pre-classification of snow free areas to reduce false classification of fractional snow cover pixels as snow free pixels during the pre-classification step; 2) adapt the auxiliary layers used for the forest canopy correction and investigating the feasibility to account for changes in the forest cover from 2000 to 2022; 3) further develop and improve the cloud screening method; and 4) adjust and homogenize the SCFV and SCFG retrievals and associated uncertainty estimations from Terra MODIS and Sentinel-3 SLSTR data. In this presentation, we will show details on the recent developments, highlight the improvements, and demonstrate the impact on the resulting SCFV and SCFG products, which are planned to be released as snow_cci SCFV and SCFG CRDP version 3.0 from Terra MODIS and Sentinel-3 SLSTR data in summer 2023.

40 Years Times Series of Global Snow Cover Fraction Based on AVHRR Data- First Analysis and Results within ESA CCI+ Snow Project

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Snow cover has critical implications for the climate and hydrology of regions, is a major component of the water cycle in most areas of the word. It affects a variety of climate process and feedback mechanisms, hydrology management, weather forecasting. The European Space Agency (ESA) Snow Climate Change Initiative (CCI+) projects provides long-term (40-years), global time series of daily snow cover fraction data derived from AVHRR satellite data. Compared to the Snow CCI+ snow cover fraction Version 2.0 products, snow cover fraction Version 2.1 (SCFG & SCFV) incorporates the significant difference in cloud cover mask using a new cloud detection method. Due to the same snow cover fraction retrieval method employed in Version 2.0 and Version 2.1, there was some possible changes in snow cover mapping in Version 2.1. Using these two long-term snow cover fraction products (SCFG & SCFV), we analyze how changes the cloud cover masks globally affect the snow cover fraction products in different regions and time periods. In addition, influence of using multiple sensors in reducing cloud cover was investigated using two versions (2.0 and 2.1) snow cover fraction. Through our analysis, the application of new cloud cover masks generated notable differences of snow cover fraction distribution in some regions. Using snow cover fraction data from multiple sensors, we demonstrate that the cloud coverage in both snow cover products (SCFG & SCFV) reduced depending on how many sensors used relative to Version 2.0 snow cover fraction. In most of regions, the timing of peak snow cover extent was slightly shifted and the cloud cover percentage in the monthly snow cover extent series is also mitigated.

New 38-Year Time Series of Daily, Global Fractional Snow Cover Maps

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The ESA CryoClim project previously developed a binary snow cover product for long-term systematic climate monitoring. The algorithm is based on fusion of AVHRR GAC and SMMR + SSM/I + SSMIS data. The product set consists of a time series (1982-2015) of daily, snow cover maps of 5 km spatial resolution with full global coverage independent of clouds and polar-night darkness. The ESA Climate Change Initiative (CCI) Snow ECV project has now developed an advancement to a fractional snow cover (FSC) product.

The original binary algorithm is based on a hidden Markov model (HMM) simulating snow states based on the satellite observations. The model is described by the different states and the possible transitions between these states. The states are given by probability density functions and the transitions by transition probabilities. A Viterbi algorithm is used to find the most likely snow cover sequence throughout the hydrological year at each grid cell. The HMM solution represents not only a multi-sensor model but also a multi-temporal model.

The advancement from binary to fractional snow cover has followed two main paths: First, we introduced more HMM states to be able to classify the snow cover into 10% FSC intervals. However, introducing 100 states to obtain 1% FSC intervals would not give a stable model. For obtaining higher precision, we have interpolated between HMM states using a secondary Viterbi sequence. The two probabilities are used as weights to estimate the FSC.

The algorithm has been implemented to run on a supercomputer as three components. The optical and passive microwave radiometer (PMR) data are processed in two processing chains giving the probability of snow from each type of data, respectively. The probabilities are applied in the HMM multi-sensor multi-temporal model generating the fractional snow cover map. The map also includes a per-grid-cell estimate of the FSC uncertainty. A new 38-year time series (1982-2019) of daily, global products was generated recently and will be made freely available to the climate community.

Two different validation approaches have been applied. The first was based on using in-situ data from stations (points) and snow courses, following the same approach as in past CryoClim activities. The other approach closely followed the validation technique developed by the Snow CCI project of using classified high-resolution data based on Landsat imagery as a reference. Based on the in-situ data approach, very similar results to those obtain previously for the binary product, were found. Yearly overall accuracy was found to be mostly between 90 and 94%, with some exceptions. Using Landsat data, the overall accuracy was found to be high with an RMSE in the order of 16% and a bias lower than 2.4%. For the FSC uncertainty estimates, a general overestimation of 2-3% was found.

Evaluation of Snow Cover Extent Products Against In-situ Snow Depth Measurements Within ESA SnowPEx+

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Satellite remote sensing enables the derivation of comprehensive information on snow cover. Analysis of the differences between the available EO-based global/continental snow products is of great interest from the users' perspective. The ESA SnowPEx project was initiated in 2014, with the aim to evaluate different snow products featuring Snow Cover Extent (SCE) and Snow Water Equivalent (SWE) by means of intercomparison and validation against reference data. The project produced a detailed analysis on the performance of different snow products and developed a consistent protocol for doing that. In the subsequent project SnowPEx+, we continue these activities.

Here we focus on in-situ validation for the new set of SCE products for years 2014-2020. Snow Depth was collected from archives maintained by Global Historical Climatology Network, by WMO distributed by ECMWF, by All-Russian Research Institute of Hydrometeorological Information and by the Chinese Academy of Science. Together these datasets cover the seasonal or permanent snow-covered areas. An important part of the work was the quality control made for the in-situ data, which is also described here.

SCE products provide information on (i) viewable snow (i.e., snow retrieval relates to what is seen from above the canopy, referred as SCEV) or (ii) snow-on-ground (also under canopy, referred as SCEG). For SCEV, it is not reasonable to compare the snow information against at-ground snow depth measurements; therefore, validation for SCEV is carried out only for open or sparsely forested areas. SCEG products are validated also in forests. Furthermore, some SCE products provide Snow Cover Fraction (SCF, %) within a product pixel while most products provide binary snow/no-snow information. Since the in-situ features only snow depth, not SCF, it was necessary to convert any snow information into binary snow/non-snow data and then use these in the comparisons. We used protocol from SnowPEx in doing this. After binary conversion, a contingency matric between in-situ data and SCE-data is generated and generally applicable statistical measures are calculated.

We present the validation results for twelve Global/Northern Hemispheric snow products. The results are presented for yearly quarterly seasons for forested and non-forested area. SnowPEx does not try to identify the 'best' product but seeks information on the potential areas or seasons that are challenging/successful for different products.

Poster Session II

Chair: Helga Weber

SnowPEx+: Results of the Intercomparison and Validation of Northern Hemispheric Snow Extent Products 2015-2020

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Satellite observations are the only means for timely and complete observations of the global snow cover. A range of different satellite snow products is available, the performance of which is of vital interest for the global user community. We provide an overview on goals and activities of the SnowPEx+ initiative, dedicated to the intercomparison of northern hemispheric and global satellite snow products, derived from data of long-term operational as well as recently launched satellites. SnowPEx+ is the continuation of SnowPEx (2014-2017), carried out as an international collaborative effort under the umbrella of Global Cryosphere Watch / WMO and funded by ESA.

SnowPEx+ focuses on two parameters of the seasonal snowpack, the snow extent (SE) from medium resolution optical satellite data (Sentinel-3, VIIRS, MODIS, AVHRR, etc.) and the snow water equivalent (SWE) from passive microwave satellite data. This presentation will focus on the intercomparison and validation of snow extent products. Overall, 15 hemispheric and global SE products (binary and fractional SE) and two SWE products are participating in the experiment. For intercomparison, daily SE products are transformed to a common map projection and standardized SnowPEx protocols are applied, elaborated by the international snow product community. The SE product evaluation applies statistical measures for quantifying the agreement between the various products, including the analysis of spatial patterns. Validation of SE products uses as benchmark high resolution snow maps from about 150 globally distributed Landsat scenes acquired in different climate zones, under different solar illumination conditions and over various land cover types. This snow reference data set, based on various retrieval algorithms, is generated, and evaluated by the SnowPEx+ High Resolution Snow Products Focus Group. In-situ snow data from several organisations in Europe, North America and Asia are also used for validating the satellite SE and SWE products. We provide an overview on the snow products, present the validation and intercomparison protocols, and report and discuss the results from the intercomparison and validation of various snow products.

Towards a Northern Hemisphere Land Surface Temperature Time Series to Support Permafrost Modelling

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Northern high latitudes have experienced pronounced warming throughout the last decades with remarkable temperature peaks, especially during winter and springtime. Due to Arctic Amplification, the Arctic region is warming thrice as fast as anywhere else. The warming affects the sensible ecosystem, vegetation dynamics and the cryosphere (sea ice, snow and permafrost). Land surface temperature (LST) is a crucial parameter for the interactions between Earth's surface and the atmosphere. It plays an important role in ecological and climate change, and in the hydrological cycle, e.g. it influences the first day of snow as well as the snow melt-out day. Hence, LST is a key variable to explain changing snow cover duration. On a global scale, observation of LST is only available from very few in-situ stations or climate models with coarse spatial resolution. Both data sources are not sufficient to model small-scale effects in ecosystems or dynamics of permafrost layers on large areas. In contrast, LST information retrieved from satellite data has high spatiotemporal coverage. To retrieve statistically significant changes of Essential Climate Variables (ECV), a time series of at least 30 years is needed. Only data of the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA and MetOp satellite series cover a sufficiently long period of more than four decades. The AVHRR Global Area Coverage (GAC) data set starting in 1981 will be used to produce a 40-year LST time series. AVHRR's two thermal infrared channels allow to apply the split-window method to reduce the atmospheric effect and retrieve LST.

Permafrost is a key component of arctic ecosystems and is highly affected by climate change. The thawing of the permafrost impacts the stability of the bedrock, damages infrastructures and releases large quantities of organic carbon. Permafrost models are an important addition to borehole measurements to monitor the status of the permafrost at a hemispheric scale. LST is an important input variable for permafrost models. We will show first results of LST dynamics and snow cover duration for a selection of regions in the northern hemisphere.

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Ground-based Observations of the Surface Temperature of Snow over Complex Topography for the Assessment of Future Thermal Infrared Earth Observation Missions

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The CNES/ISRO satellite Trishna will provide high resolution thermal-infrared (TIR) images at global scale every 3 days starting from 2024. This represents the first opportunity for intensive monitoring of the snow surface temperature in areas of complex topography, where it is limited by the coarse resolution with respect to the topography or by the long revisit time of the sensors currently in orbit. However, the retrieval of surface temperature from satellite observations is complicated by the presence of different slopes and orientations, the complex atmospheric conditions of mountainous areas and the fast-evolving nature of snow. In this context, we aim to provide accurate, high resolution and extensive ground-based observations of the snow surface temperature to validate future Trishna products. We set up a validation site at the Col du Lautaret site in the French Alps. In-situ instruments include two TIR cameras, one fixed and one on-board of UAVs, three TIR radiometers and standard thermometers. Ground-based observations are corrected for multiple instrumental and topography related biases and compared to Landsat 7/8/9 and Ecostress images. Here we present an inter-comparison of the surface temperature observations from all these sources and draw the first conclusions about the accuracy of existing TIR satellite products, that only partially account for the presence of complex terrain features and varying microstructural snow properties. The results stress the importance of accounting for the local topography in the retrieval of the surface temperature by satellite on tilted snow-covered areas.

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The Lake Ice Extent Information On Hemispherical Scale

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Information on seasonal lake is important in many aspects: weather prediction, transport, safety issues, lake ecology and water quality. Additionally, lake ice is sensitive to temperature fluctuations and long-term temperature trends. It is therefore a valuable indicator of climate warming, which will likely have dramatic impacts on lake ice phenology in northern latitudes.

Northern Hemisphere Lake Ice Extent (LIE-NH) is one of the Copernicus Global Land Service (CGLS) near-real-time daily products. The LIE-NH is based on Sentinel-3 Land Surface Temperature Radiometer (SLSTR) data and is provided in 500m pixel size. It utilizes a new method, ICEmod, developed at the SYKE, for assessing lake ice extent (LIE) using optical satellite data. The method is based on multidimensional Gaussian distributions calculated for training data using several reflectance and thermal bands and their-related indices. Importantly, ICEmod includes cloud detection as a part of classification, thus eliminating the need for separate cloud masking.

The LIE-NH is subject to a spatially and temporally extensive validation during autumn 2022 using over 2600 cloud-free or almost cloud-free high-resolution Sentinel-2 Multispectral Instrument (S2 MSI) images. The S2 MSI reference dataset covers 135 lakes, 45 lakes per each continent (Europe, North America, Asia) covering different types of lakes (water quality, size and location) and at different ice status. The validation period is from January 2020 to May 202 providing information about the product accuracy throughout the year. The S2 MSI-based LIE products were created using a simple tree decision model, which was trained with carefully quality checked training data. This training data consisted of 44 S2 MSI images including over 38 million classified (ice or water) pixels. The cloud class will be validated using the collection of quality checked S3 SLSTR- based cloud layer.

In this presentation we will i) shortly explain the ICEmod principles and ii) describe the protocol and results for LIE-NH product validation. Additionally, we will present the newly released Lake Ice Service developed under the EU funded Arctic PASSION project. Lake Ice Service collects lake ice information from multiple sources and visualizes the information in a format that is easy to access and understand. This information will be exploited by citizens and local communities as well as for scientific purposes.

A Spaceborne Snow Mission Concept Using P-band Signals of Opportunity

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Mountain watersheds play an outsized role in global hydrology and function as "water towers" to supply downstream needs that serve a large portion of the global population and its economy. Mountain snow, in particular, provides a key source for agricultural and urban water supply, hydropower, recreation, and ecosystem services. These historically reliable virtual reservoirs are highly susceptible to both climate change drivers and socioeconomic pressures. Despite the need for mountain snow water equivalent (SWE) information, current spaceborne capabilities are lacking in their ability to track the seasonal evolution of mountain snow across the necessary spatial and temporal scales. Properly capturing seasonal snow dynamics are necessary to constrain models and their projections of current and future snow-derived water resources. This presentation reports on the continued development of a new mission concept for the remote sensing of terrestrial snow. A P-band Signals of Opportunity (SoOp) synthetic aperture radar (SAR) concept is proposed to take advantage of signals already being broadcast by existing communication satellites. The phase and amplitude of the signal reflected from terrestrial surfaces can be measured using a constellation of receivers on SmallSats. Long wavelength P-band signals are attractive due to their ability to penetrate deep snow and forest canopies found in mountain environments, with limited sensitivity to seasonally-varying snow grain microstructure, stratigraphy and liquid water content that can confound retrievals at shorter wavelengths. Measured phase changes in the reflected signal yield SWE or snow depth estimates using well-developed interferometric techniques. The measured amplitude of the reflected signal yields retrievals of rootzone soil moisture, which provides additional insight into the antecedent conditions before snow and the partitioning and fate of snow meltwater into soil water storage vs. runoff. The concept proposes using a formation flight of SmallSats to allow the use of interferometric SAR processing to obtain a spatial resolution of a few hundred meters and a swath width of 100 to 200 km. Results are reported on how a P-band SoOp-SAR mission concept would provide new insight into the dynamics of seasonal mountain snowpacks and provide complementarity to other snow mission concepts.

SAR and Passive Microwave Fusion Scheme: a Test Case for Sea Ice Classification

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Earth's surface and sea ice in particular can be monitored by different sensors mounted on various satellite platforms. At present, the most commonly used source of information about sea ice conditions is remote sensing data, especially images obtained from synthetic aperture radar (SAR) and passive microwave (PM) sensors. Each of these sensors has some limitations that can be a huge obstacle towards reliable sea ice classification and characterization. SAR provides high-resolution imagery, however, it is significantly affected by thermal and speckle noise, which decreases the visual interpretation. PM on the other hand is less affected by noise and guarantees better spatial coverage, however, at the expense of resolution. Nevertheless, a reliable fusion of available sensors together can solve some challenges since various sensors provide a vast amount of diverse information regarding the study area and offer great potential in Earth Observation applications. Taking into account the significant differences in spatial resolution as well as in measured quantities, the combination of these sensors can be quite challenging. In this study, we illustrate the advantages and limitations of each sensor type. We introduce a fusion scheme that allows us to combine SAR and PM data as well as to select relevant information using an unsupervised and efficient method based on Graph Laplacians. Moreover, we explore the potential of multiclass sea ice classification employing SAR and PM multi-sensor data sets simultaneously and separately, in order to evaluate the complementarity of each sensor. Experiments illustrate the flexibility and efficiency of the proposed approach that exploits information selection and parallel classification using AMSR2 and Sentinel-1 data combination.

Framework For Snow Cover Monitoring Using A Coherence-Based Approach

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With the increase of operational SAR missions, like ESA Sentinel-1, the benefits of SAR-data for environmental monitoring compound with access to higher temporal resolution and long-term mission fidelity. One area in which these developments are especially beneficial is the realm of high latitude snow cover monitoring. In this environment, monitoring in general, is hampered by the common partial to full cloud cover in the entire circumpolar region. The immediate benefit of the use of SAR data for the generation of snow-related products in these areas is the cloud penetrating properties of microwave-based remote sensing.

This study introduces a coherence-based framework for determining snow cover using the accessible C-band SAR data of the ESA Sentinel-1 mission, intended to be the basis of an automated, continuous snow cover product. By employing a random forest classifier to changes in coherence, between acquisition pairs or mosaics, development and changes in snow cover can theoretically be detected down to a multilooked resolution of Sentinel-1 image data of 25x25m. These results are then validated against any cloud free areas in a NDSI composite of the closest temporally available Landsat / Sentinel-2 images. Due to the overlap of SAR data at higher latitudes as well as the temporally separated nature of coherence data, the end product is on the form of a multitemporal-mosaic, with each classified pixel indicating its source data.

A series of images from the spring season of 2017 have been used for determining the viability of the method, covering the north of Sweden, with good results for both pre-thawing and snow melt. The results show high fidelity with some deviations occurring in areas with dense vegetation, in some cases of bare mountain areas as well as in areas with steep topography. Steps taken to alleviate these problems include the use of a landcover product to further improve classification as well as statistical filtering for generation of large spatial scale products in lower resolutions.

The main purpose of this study is to show the viability of a coherence-based method for snow cover detection and monitoring as a foundation for a fully automated, self-validating and self-improving process for generating a continuous snow cover product.

A Fast and Low-Cost Instrument for Snow Roughness Measurements in the Field

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When the snow blanket is observed from above, the superficial roughness of the snow is an important parameter used to characterize the snowpack state. In fact, the snow roughness depends on several factors such as the type of the snow deposition and the superficial metamorphism due to the local weather conditions. The processes that drive the changes in the snow surface roughness are often difficult to be modeled due to both the different scales at which they operate and the overlay of their effects. In this work, we present a system for snow roughness measurement. The system is made up of digital camera and a black Forex panel. The whole system has been designed for being low cost and portable; and will be distributed as an open-source Python software. The system is based on the coregistration of the photos taken at the panel on the field with a reference scaled image with pixel size of 0.05 mm. On the panel is impressed a Charuco pattern to optimize the image matching. In detail, the coregistration process is done by computing the homography, whose parameters are estimated exploiting automatic key-points matching. Among all methods for key-points extraction, we used the scale invariant feature transform (SIFT) because of its robustness and recognized efficiency. After key-points extraction, the matching has been performed using a brute force matching (BFM) approach. The proposed system has been tested under different conditions, showing to be an effective and easy approach to snow surface roughness measurement, as well as robust. In detail the roughness parameters obtained with the panel are compared and validated with a time series of Lidar DSM acquired on the Weissfluhjoch snow test site managed by SLF showing good agreement in case of low roughness.

Improving GlobSnow Snow Water Equivalent Retrieval With Spatially And Temporally Varying Snow Densities

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Snow water equivalent (SWE) is an important property of seasonal snow and estimates of SWE are required in many hydrological and climatological applications, such as climate model evaluation and forecasting freshwater availability. SWE estimates can be made using brightness temperature measurements from passive spaceborne radiometers. The radiometer based GlobSnow SWE retrieval methodology, which assimilates synoptic weather station snow depth measurements into the retrieval, has improved reliability and accuracy when compared to stand-alone radiometer SWE retrievals. To further improve the GlobSnow SWE retrieval methodology, we present an approach for implementing spatially and temporally varying snow density fields into the GlobSnow SWE retrieval. Until now the GlobSnow SWE retrieval has used constant snow density throughout the retrieval despite the location, snow depth or time of winter and this constant snow density is a known source of inaccuracy in the retrieval.

Spatially and temporally varying snow density fields have been created using manual snow transect measurements from Finland, Russia, Canada and the eastern USA and automated measurements from the western USA and Canada. Three different versions of varying snow densities are tested over a 10-year period (2000-2009). These versions use two different spatial interpolation techniques, ordinary Kriging interpolation and inverse distance weighted regressing (IDWR). Implementing any of the three versions into the SWE retrieval was found to improve retrieval when compared to the baseline GlobSnow v3.0 product and differences between different versions are relatively small. The overall best results were obtained by implementing IDWR interpolated densities into the algorithm. Implementing these IDWR interpolated snow densities in the SWE retrieval reduced RMSE (Root Mean Square Error) and MAE (Mean Absolute Error) by about 4 mm and 5 mm when compared to the baseline GlobSnow product, respectively. Additionally, implementing varying snow densities into the SWE retrieval improved the accuracy of snow mass estimates at the hemispheric scale when compared to the baseline product and the product post-processed with varying snow densities.

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CLIMATE CHANGE RESEARCH

Mountain snow

Chair: Helga Weber

The Mountain Cryosphere in a Changing Climate: a View from Within Science-Policy

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In 2022, the Intergovernmental Panel on Climate Change (IPCC) adopted the Working Group II contribution to the sixth assessment (AR6) on impacts, adaptation and vulnerability, in which a cross-chapter paper dedicated to a synthesis assessment on "mountains" was included. Together with the IPCC's Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), adopted by the Panel in 2019 and which featured a chapter on "High Mountain Areas", meant that – for the first time in almost 30 years - 'mountains' have a dedicated space in the IPCC reports. This not only stimulated scientific research efforts in response to assessment knowledge needs but also inspired engagement in advocacy efforts to elevate mountains at the so-called science-policy 'interface'. This talk presents some observations and reflections based on this experience from a standpoint and role as lead author involved in the IPCC's AR6 syntheses efforts on mountains, but also that of a network facilitator that straddles the science-policy space on mountains. The talk highlights some of the research gaps identified in AR6 that can serve as a useful springboard for ongoing and future assessment efforts by the mountain research community, as well as offer entry points for broader outreach in society and policy. Building on previous assessments, while improving the existing knowledge base, is key to substantiating options for decision-making and actions going forwards, making a case for considering the mountain cryosphere as an integral component of the wider mountain context in which the mountains and lowlands are integrally linked.

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Snow Cover Dynamics In The Hindu-Kush Himalayas Using Improved Modis Snow Products

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Snow cover is an important element of Earth's climate, hydrological cycle and energy budget, thus regarded as a proxy indicator of climate change (Robinson et al., 1987, Kropacek et al., 2010). The Hindu-Kush Himalaya (HKH) region, often referred to as the third pole, is the fundamental source of discharge for 10 major Asian rivers (Immerzeel et al., 2010; Gurung et al., 2011), supporting life and livelihoods of more than 1.3 billion people (Jianchu et al., 2007) and known to be a climate sensitive region (Bednorz et al., 2004, Beniston et al., 2003; Bradley et al., 2006, Barnett et al., 2005). For every °C increase in temperature, the snowline is predicted to rise by about 150m (Beniston et al., 2003). In this study, we analyze and compare the temporal and spatial variability of Snow Cover Area (SCA) and Snow Line Elevation (SLE) across the 10 major basins of HKH using an improved MODIS snow product (M*D10A1GL06) for 2002-2019 (Muhammed et al., 2020). We found the North-Western basins to have highest annual SCA followed by North-Eastern and Central basins, with Brahmaputra (Central) sharing similar characteristics with North-Eastern basins. The annual snow cover for North-Western basins is observed falling steeply after February with minimum during August and increasing thereafter unlike North-Eastern basins which have plateaued minima around monsoonal months; Southern basins don't show any significant patterns. Overall highest snow cover is found during winter season. The annual SLE in HKH is clustered at around 5300m. Overall monthly SLE is highest for the months of July-September. We found the snow cover of westerly impacted basins to be generally higher than ones impacted by monsoon.

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Next-Generation Snow Products For Entire Mountain Ranges

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Snow in alpine areas is arguably a crucial water resource for downstream communities and ecosystems. Snow monitoring is critical for water and risk management, with applications ranging from hydropower generation to outdoor activities. Most operational snow monitoring approaches on the catchment scale estimate snow cover extent (SCE), snow depth (HS) and snow water equivalent (SWE) in a coarse spatial resolution of 100 m to several km. In alpine areas, however, this low resolution fails to capture highly variable snow distribution patterns caused by pronounced topographic variations. In this work, we present ExoLabs innovative approach to monitor daily SCE, HS and SWE for entire mountain ranges in a 20 m spatial resolution. Mapping SCE involves multi-satellite observations paired with machine-learning based spatiotemporal modelling. Subsequent modelling of HS further includes gaussian process interpolation of ground measurements while accounting for fine-scale topographic variations. Based on HS, the SWE is modelled using a semi-empirical multilayer model accounting for snow compaction. All these snow products are validated against independent reference data and demonstrate the value of novel approaches to capture snow water resources at an operational level.

Snow Cover Classification over Mountainous Terrains at Optical Wavelengths by Machine Learning: Existing Challenges and New Opportunities

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With the recent technical improvements in all kinds of data recording instruments, the era of big data has revolutionized the earth sciences from data-poor field to data-rich field. And in parallel, machine learning algorithms have become more prevalent for environmental parameter retrieval in remote sensing. Snow cover is an important physical element of the Cryosphere, and two major snow-related parameters can be derived by satellite observations. The first parameter is the snow water equivalent, which is extracted from passive/active microwave measurements. The second one is the snow cover extent, provided either in binary format (i.e., snow/no snow) or as subpixel snow cover maps by means of optical remote sensing. Even though snow cover monitoring by traditional model-based remote sensing techniques at optical wavelengths is well-established, there still exist several challenges and limitations such as cloud and canopy obscuration, cloud-snow confusion at land-snow boundary over snow covered areas, reduced reflectance at optical-infrared wavelengths due to topography/relief- or cloud-casted shadows, etc. In this presentation, it is aimed to introduce the initial results of our efforts for binary snow cover classification on Sentinel 2 imagery over regions with complex and heterogenous topography by random forest (RF) algorithm. The selected study areas are over European Alps, Tatra Mountain Range, and Kaçkar Mountains in the north-eastern Turkey. For each region, a single Sentinel 2 tile is selected, and three images on that tile acquired on different dates (representing different morphological states of snow, i.e., fresh, settled, and melting snow) are downloaded and preprocessed. The preprocessing stage involves resampling of Sentinel 2 bands to 20 m, as well as atmospheric/topographic correction by Sentinel 2's own scene processing module Sen2Cor. Various predictor variable combinations are employed in the model building stage and their impact on the predictive performance of RF modelling is investigated. The effects of training data size and atmospheric/topographic correction are also investigated. Even though snow detection over dense forests still remains as a major limitation, the overall results indicate that i) larger training sample size leads higher rates of accuracy, ii) the inclusion of PC bands gives better snow classification performance under cloud shadows, iii) atmospheric/topographic correction yields improved snow detection. The predictor variable combination including the first three PC bands extracted from the atmospherically and topographically corrected Sentinel 2 bands together with NDSI, NDVI and NDWI provides the best classification performance with overall accuracy of 97% and kappa coefficient of 0.89.

Near-Real-Time Snow Cover Fraction Estimation using Linear Spectral Unmixing of Sentinel-2 MSI Top-of-Atmosphere Reflectance Data

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The seasonal snow cover is an important resource in mountain regions, the monitoring of which is crucial for snow hydrology, water management, tourism, and natural hazard mitigation. Alpine snow is also an important source of headwater for drainage basins downstream. AlpSnow (2020-2022) is a science activity within ESA's Alpine Regional Initiative, addressing the development of novel Earth Observation techniques and algorithms for the generation of innovative snow products optimized for specific scientific and operational applications. In this presentation we present a method for monitoring fractional snow cover in mountain areas exploiting the spectral bands on high resolution satellites such as Sentinel-2 and Landsat-8/9.

The fractional snow cover is estimated from Sentinel-2 MSI top-of-atmosphere reflectance data through linear spectral unmixing. All 13 spectral bands of the Sentinel-2 multi-spectral instrument (MSI) are used for this estimation. Fully snow-free and fully snow-covered endmembers are detected in the scene by using a pre-classification step which combines a hierarchical decision tree and a similarity measure. To estimate the FSC at a query point several near-by fully snow free and fully snow covered endmembers are selected. The linear unmixing problem is then solved iteratively using different combinations of these endmembers accounting for different illumination conditions and shaded areas. Finally, the snow cover fractions from the different endmember combinations are merged and the associated uncertainty is derived. The algorithm has been successfully applied on scenes in different environments and climate zones in the world, including Alps, North America and High Mountain Asia. The performance has been assessed through intercomparison with very high resolution satellite data (Worldview), with products from standard algorithms (e.g Salomonson and Appel; 2006) as well as with products from the Copernicus High Resolution Snow and Ice Service. The procedure is fully automatic and is operating in near real time for the Alps using Sentinel-2 data during the winter period 2022/23. Examples of the prototype service will be presented.

High-resolution Wet Snow Mapping in the Karakoram: A Probabilistic Method Based on SAR Imagery and Topography Data

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Mapping wet snow cover (WSC) in the Karakoram region is of particular interest, as the WSC is a key element in various applications such as hydrology, alpine ecology, and local meteorology. To map the WSC, SAR images acquired by the co-polarized (VV & VH) Sentinel-1 satellite show distinctive advantages because of the high spatial-temporal resolution, wide image footprint, and invulnerability to clouds. On SAR images, a widely used method for WSC detection is to set hard thresholds on backscattering ratios (Rbsc), as wet snow shows respectively lower backscattering coefficient than dry-snow or snow-free surfaces. Although using an absolute threshold value has been shown effective in WSC detection, it was found that the threshold value may vary on different land cover, surface roughness, and snow wetness. Therefore the operational WSC mapping on a very large scale is hampered.

In this work, we propose a probabilistic method to map the WSC in the Karakoram using Sentinel-1 imagery and Digital Elevation Models (DEM). Instead of using an absolute value as a hard threshold, our method transforms Rbsc into wet snow probabilities using a Gaussian Mixture Model (GMM), and incorporates the elevation information by calculating the probabilities of having wet snow at different altitudes. Based on both probabilities, joint probability for wet snow is calculated, and wet snow maps are generated by setting thresholds on the joint probability. Using the probabilistic method, we can better account for uncertainties caused by surface properties, and in the meantime accommodate the complex terrain in alpine regions.

The proposed method was validated using snow maps generated from Sentinel-2 optical images over selected regions. We also compared it with the classical hard-thresholding method to better understand the advantage of the proposed method. The developed probabilistic model was then applied to map the WSC in the Karakoram using Sentinel-1 SAR images acquired during 2017-2020, and the obtained map was cross-checked and interpreted together with simulated metrological data. The results showed clear annual changes in snow melting patterns and strong correlations between the changes and local climate variations.

In conclusion, our work showed a feasible implementation of regional WSC mapping in the Karakoram, and demonstrated a new framework of fusing multi-mode data for wet snow detection under the perspective of probability.

Remotely sensed snow height

Chair: Colleen Mortimer

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Machine Learning and LiDAR Snowheight Maps from UAVs Reveal Clusters of Snow Variability in a Sub-Alpine Forest.

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Snow plays a crucial role in the hydrological cycle as it serves as an intermediate storage of winter precipitation and renews groundwater reserves. It is therefore of central importance for, among others, our drinking water supply and agriculture. Snow interacts with its environment in many ways, is constantly changing with time, and thus has a highly heterogeneous spatial and temporal distribution. Therefore, modelling snow variability is difficult, especially when additional components such as forests add complexity. To increase our understanding of the spatiotemporal variability of snow as well as to validate snow models, we need reliable validation data. For these purposes, airborne LiDAR surveys or time series derived from snow sensors on the point scale are commonly used. However, these are disadvantageously limited to one point either in space or in time. In this study, we profited from current advances in LiDAR and drone technology, as well as machine learning, to bridge this gap. We present a new dataset on snow variability in forests for the Alptal, a sub-alpine, forested valley in the pre-alps, Switzerland. The core dataset consists of a dense sensor network, repeated UAV-based LiDAR flights and manual snow height and density measurements. Using modern machine learning algorithms, we determine seven clusters of similar spatiotemporal behaviour regarding their snowheight. These clusters are characterized and further used to derive daily snow depth and snow water equivalent maps. By using the latter, we obtain spatially continuous key hydrological variables. The results underline the strong relation between topography and canopy cover to snow accumulation and ablation. However, we show that the spatiotemporal variability of snow occurs in clusters that reoccur in space. The presented dataset and derived products are the first to our knowledge that provide daily, high-resolution snow height and hydrologic variables based on field data. The results of this study can therefore improve our understanding of the spatiotemporal variability of snow in forested environments. Moreover, it is ideally suited for the validation of modern snow models.

Tracing Snow Cover Dynamics Using 4D Level Sets on Near-Continuous Terrestrial Laser Time Series Scans

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Accurate monitoring of snow cover dynamics contributes to the understanding of the changing cryosphere, enables the characterization of hydrological processes, and can help managing natural hazards. However, the high-mountain topography and the indistinctness of snow upon the surface turn such monitoring to a challenge. Furthermore, processes which occur at different rates and at various spatial extents, like deposition through snow drift, cannot be recognized at a single point in time. Therefore, they cannot be easily separated, quantified, and characterized. Recent years have seen an increase in near-continuous 3D observations that capture Earth surface dynamics at a local landscape scale. Such measurements enable advanced detection of surface changes. For example, by identifying similar change histories, surface modifications through time can be delineated. This way, changes that originate from different processes but coincide spatially and/or temporally are still extracted. Such methods benefit from the combination of the temporal domain with the spatial one. However, they do not consider the spatiotemporal variability of surface activities. In this study, we propose to trace snow cover dynamics in near-continuous terrestrial laser scans by utilizing a level set framework. We formulate the extraction of changes as a minimization problem where the zero level-set represents their borders. Using a fully automated 3D region-based level-set approach, we extract entities that share similar change rates at a specific point in time directly from the point cloud. This way, we identify snow cover dynamics in 4D which may be indistinguishable in a single scan, but have a distinct signature through time. We demonstrate the proposed method on hourly terrestrial laser scans of snow cover acquired at the Zugspitze (Schneeferner) in Germany over five days in April 2018. These scans feature snow melt and compaction, avalanches, and anthropogenic modifications (e.g., snow farming). Results show that using the proposed method, we are able to trace different phenomena with a variety of spatial and temporal properties (e.g., timing, duration, magnitude, change rate, spatial scale). These are extracted simultaneously across multiple epochs, depending on their duration and in a single analysis process. The focus on geometric properties through time suggests that we are unbound to predefined types or numbers of surface processes. Thus, the proposed method paves the way to a general monitoring which can capture a large variety of surface dynamics in complex cryospheric scenes through time.

Spaceborne Snow Depth Measurements From ICESat-2 Laser Altimetry

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Snow depth measurements such as from weather stations or targeted remote sensing campaigns mainly exist in easily accessible places in wealthy regions of the Earth. In remote, mountainous areas, the lack of inexpensive methods to measure snow amounts strongly limits the monitoring of supplies for drinking water, irrigation, hydropower or flood hazards for a large part of the Earth's population. We show that data from the spaceborne laser altimeter ICESat-2 can provide high-quality snow depth measurements when combined with an accurate digital terrain model (DTM). ICESat-2 measures the surface elevation of the Earth along profiles with a revisit time of three months, whereby ground tracks are shifted in space between overpasses in the mid-latitudes. Data from three field studies in Norway and Finland show that snow depths derived from the freely available ICESat-2 ATL03 data product match the vertical accuracy of snow depth data acquired with a drone-based lidar sensor and measurements at a nearby meteorological station. This is also true for forested areas where snow amounts are difficult to measure. Given cloud-free conditions and a very-high-resolution DTM, one ICESat-2 overpass yields six parallel snow depth profiles with ~1 m along-track spacing and a snow depth accuracy at centimeter- to decimeter-scale. Lower-resolution DTMs or the presence of moderate elevation bias or spatial shifts in the DTM may still allow for regional snow depth averages but require more extensive data processing and spatial binning. The method is thus limited by the availability of a high-quality DTM, whereby the absence of elevation bias is far more important than the spatial resolution of the DTM. A further limitation is the satellite's low repeat time combined with the sparse ground track pattern at mid-latitudes, resulting in few snow depth profiles over the course of one winter – in particular in cloudy areas such as Western Norway. However, an ICESat-2-derived snow depth profile can provide valuable information about the spatial distribution of snow depths within a region that is not captured by point-based snow depth time series from a weather station. With the quality and accuracy of global DTMs ever improving, we expect that the accuracy of snow depth measurements derived from spaceborne laser altimetry will continue to improve in the future and provide currently lacking snow depth data in remote and mountainous areas.

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Long time series of snow cover based on AVHRR and Sentinel-3

Chair: Sari Metsämäki

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Less White: Decreasing Alpine Snow Cover derived from a 40-year AVHRR Snow Climatology

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Satellite-derived, long-term snow cover extent (SCE) documents broad-scale climatic variability and change of the cryosphere. SCE is a highly dynamic Essential Climate Variables (ECVs; e.g. GCOS-200, 2016) for the cryosphere used to assess its current state, long-term changes, and the rate of these change. Thus, SCE time series fill essential knowledge gaps on past snow occurrences and support our understanding of spatiotemporal variance in snow cover. This is of special interest in mountainous alpine areas, such as the European Alps, which are hotspots of biodiversity and particularly vulnerable to climate change. However, a weak correlation was found in summer of greening predominated in warming areas and snow cover recession, though significant (Rumpf et al., 2022).

This contribution presents a spatiotemporal analysis for the European Alps based on a novel, public accessible Level-2 and -3 fractional snow cover (FSC) data set (1981-2021) from the Advanced Very High Resolution Sensor (AVHRR). The FSC product is canopy-corrected, gap-filled for Level-3, and includes an uncertainty estimation as well as user-oriented quality flags, while the spatial resolution is defined by AVHRR's effective footprint size of 1.1 x 1.1 km at nadir. Data source is the extended European daily AVHRR LAC L1C data set (version v04; processed in 2022) dating from 1981 until today, hosted by the University of Bern, Switzerland. To avoid misclassification and better discriminate between clouds and snow, the newest PPS probabilistic cloud mask (PPS v2021.1 by NWSAF/SMHI, Sweden) has been applied following a sensitivity analysis. Canopy-corrected FSC has been estimated using the adapted SCAMOD method (Metsämäki et al., 2015, Weber et al., 2021).

Based on this novel data set, we analyze spatiotemporal variability in seasonal snow cover related to elevation-dependent warming and in combination with climate data provide insights into the controls of this variability. Our study is focused on the European Alpine mountain region, which is particularly vulnerable and sensitive to climate change. In addition to a decrease in snow cover duration (SCD) and spatial extent (Hüsler et al., 2014), it has been observed that temperature increases particularly rapid at the current boundary of the cryosphere (e.g., snowline region) due to the snow-albedo effect (Pepin et al., 2022 and therewithin). To assess these changes and temporal trends using the novel data set, we derived seasonal snow cover metrics for specific Alpine catchments. Seasonal and annual SCA anomaly as well as mean SCD were calculated for different elevation bands of the Alps and subregions of Switzerland over the entire time range to analyze long-term changes. The future analysis of respective climate data (i.e., temperature and precipitation) allows to determine controls of long-term variability in these highly sensitive environments.

36 Years of Daily Snow Cover Data for Europe Based on AVHRR Data: Results from the DLR TIMELINE Project

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Long time series of remote sensing data are useful analyzing the effects of climate change on planetary snow cover. Such studies have been conducted since the late 1970s relying on multispectral sensors such as AVHRR, SPOT VEGETATION, ATSR, MODIS, and NPP VIIRS. For analyzing snow cover distribution before the year 2000, data originating from AVHRR sensors are often the only available choice. These datasets come with a variety of challenges, including geolocation uncertainty, sensor degradation, platform drift, and a limitation to only 5 spectral/thermal channels. These challenges defined some of the objectives included in the DLR Timeline project, which aimed at re-processing the entire AVHRR data archive available at the German Satellite Data Archive (D-SDA) of the German Remote Sensing Data Center (DFD) of the German Aerospace Center. Throughout the last years, processors to perform calibration, geolocation and atmospheric correction, a state-of-the-art cloud mask, as well as an entire set of parameters such as LST, SST, fire hot spots, NDVI, and snow cover have been developed. This presentation will give a very brief overview about the pre-processing of the AVHRR archive, but then focus on the snow cover product developed within Timeline. The time series of processed data will be illustrated, and first results from trend analyses and additional studied will be shown.

Semantic Earth Observation Data Cube of AVHRR and Sentinel-3 SLSTR Data for Exploratory EO Analysis

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Together we prototypically implemented a semantic Earth observation (EO) data cube containing a semantically-enriched time-series of Advanced Very High-Resolution Radiometer (AVHRR) imagery from 2016-2021 and all available Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) imagery up to today (i.e. ongoing) covering the European Alps (i.e. COSMO-1E extent from MeteoSwiss). A semantic EO data cube is a spatio-temporal data cube containing EO data, where for each observation at least one nominal (i.e., categorical) interpretation is available and can be queried in the same instance. Additionally, we derived and included some essential climate variables (ECVs) for the same area using a curated time-series from the AVHRR archive at the University of Bern (1982-2021), as well as from all available SLSTR observations: normalized difference vegetation index, fractional snow cover estimation, and lake surface water temperature. The resulting semantic EO data cube implementation encompasses calibrated top-of-atmosphere reflectance values, automated semantic enrichment and ECVs from both sensors that can be queried in the same instance.

This implementation delivers climate-relevant EO-derived variables together with analysis ready data and semantic enrichment, provided in an attractive graphical user interface (GUI) and semantic querying language, called semantique. Both of these developments are generic and applicable to other sensors, EO imagery interpretations and ontologies. The GUI enables users to select a spatio-temporal area of interest and conduct a query using existing (or custom) semantic models, facilitating shareable and repeatable queries on-demand at a user's own request. Programming-free exploration and analysis of EO archives is possible that goes beyond queries for image extent and observation time, while also enabling more complex analysis via reusable and sharable semantic models. This means that in just a few clicks, users can already analyse calibrated reflectance values and/or interpreted image content for their own defined area and timespan of interest on-the-fly. For users that prefer programming, Jupyter notebook access to the semantic EO data cube is available via the Open Data Cube's Python application programming interface (API) as well as the semantic querying language's API.

Instead of providing a single domain or product-focused implementation, users can create semantic models and derived analysis that explicitly map their own ontology to EO imagery and derived interpretations, including but not limited to the domain of land ice and snow. Given further development and support, this contribution may be an asset to better facilitate EO data access and analysis, particularly in professional training and educational contexts.

Educational programs and activities

Chair: Kathrin Nägeli

From Glacier to Classroom: Peer-to-Peer Communication to Foster Curiosity in Science

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After a winter with extreme low amounts of snow on all Swiss glaciers and an extraordinary hot summer particularly in western Switzerland, one could literally see the Swiss glaciers vanishing. Climate change is more noticeable in our society than ever before. Many young people in Switzerland are well informed about global climate change and want to be part of political debates and actions. However, participation and active involvement comes along with background knowledge, support from the surrounding environment and last but not least self-confidence. Some young people - in particular young women - lack this support, interactions, and access to information, or miss self-confidence to take action and adapt themselves to coming changes.

We, Girls on Ice Switzerland, strongly believe that immersion and personal experience are key for a profound understanding as well as crucial for motivation for actions and changes. We hence offer tuition-free glacier expeditions for teenage girls, where we spend an entire week on a glacier and participants return home with a very different perspective of how climate change affects our environment. This provides the basis for our school activities led by participant-scientist tandems, where we use the personal experience of a peer as a unique communication method. The expedition participants become science ambassadors for their peers and at the same time strongly increase their self-confidence. We open the floor for honest, scientific-based and diverse discussions among young students, supported by scientists and provide the basis for future interest and engagement from the students. The peer-to-peer communication as well as the interactive structure of our workshops and excursions open the floor for honest, scientific-based and diverse discussions among young students, supported by female scientists.

This contribution highlights the core values of our organisation, sheds light on all our activities (expeditions, school workshops and excursions) and most importantly, presents experience, learnings and challenges by a past participant.

Getting Inspired by the Cryosphere: A Science Program to Empower Young Women in Central Asia

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"Adventure of science: Women and glaciers in Central Asia" combines and addresses two urgent needs which persistent in Central Asia: 1) Vulnerability through climate change 2) Women empowerment in STEM fields. First, the region faces many challenges in fields such as water management and disaster risk reduction and must develop innovative adaptation and mitigation strategies to combat Climate change. Second, high disparities exist in women's condition including pay gaps, low involvement in decision-making, gender-based violence, and low access to opportunities in Central Asia (UNDP, 2016).

The program "Adventure of science: Women and glaciers in Central Asia" fosters science communication by inspiring young women for science, nature, and art. It takes young women between 18-25 years old from Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan from diverse backgrounds to a ten-day glaciological excursion (Imanalieva et al., 2021). Back in the pandemic years, Adventure of Science at home started to focus also on digital Earth technologies to empower women in science and thus support global problems. Here we will highlight both digital as well as field excursions to cover the full spectrum of the program. The excursion seeks to strengthen young women's self-confidence in their physical, intellectual, and leadership abilities through the application of art and science. The age limit targets a critical age in their education for future decision-making. The program creates a free and safe space of gender roles with a professional women-only team. The regional network is built on collaboration with local institutions and researchers, such as UNESCO Almaty and CAIAG, and international workshops. The project also has an institutional impact by encouraging local institutions to engage young female students and scientists into academic activities and research. The involvement of local researchers, mentors, and alumni network makes the program sustainable and will lead to a self-management of the program by women of Central Asia in future. The program finds a unique echo in Central Asia because of structural barriers women face in the region and because of the regions' vulnerability to climate change.

In Summary, "Adventure of Science: Women and Glaciers in Central Asia" aims to create lifelong advocates for Earth science and wilderness stewardship, and support a network for early-career scientists and beyond.

Addressing Gender Inequality in STEM: Cryospheric Excursions in Central Asia

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The Soviet Union period marked the onset of active glaciological research in Central Asian mountains. Despite being male-dominated, the cryospheric sciences became accessible for female scholars, albeit as a support of political ideology (Hulbe et al, 2010). Following the collapse of the Soviet state, the region experienced drastic political and societal changes, and many glaciological stations in Central Asia discontinued their observations (Barandun et al, 2020). The number of female workers in STEM fields has decreased, as well as the number of female students majoring in hard science. Traditional sets of norms have started to re-emerge to a varied extent in Central Asian countries, inhibiting both opportunity and retention of women in STEM fields. Moreover, young women in the region face the contradicting societal expectation based on superimposed traditional, Soviet and western values (Almukhambetova & Kuzhabekova, 2021).

To bridge the existing gender gap, the program „Adventure of Science: Women and Glaciers in Central Asia“ organises ten-days glaciological expeditions for participants from Kazakhstan, Uzbekistan, Tadjikistan, Turkmenistan and Kyrgyzstan (Imanalieva et al, 2021). The program is designed to foster the interest of young women in STEM through the scientific and artistic outdoor exploration. It offers a space free of stereotypical gender roles, and exposure to high mountainous nature under supervision of women-only professionals. The combination of mountaineering basics alongside the training on geoscience topics focuses in particular on the cryosphere and aims to strengthen participants' self-confidence in their physical, intellectual, and leadership abilities. Additionally, it creates a support network, and provides role models, which are recognized to be essential for women to persist in STEM fields.

Our contribution shows how STEM in the field of glaciology in Central Asia can be bridged by conducting hands-on, women-only excursions. This includes experimental learning, networking and scientific projects.

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EARSeL

UNIVERSITÄT BERN

OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

Glaciers

Chair: Stefan Wunderle

Automated Classification of Glacier Facies From Sentinel-2 And Landsat Data

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Alpine glaciers are sensitive indicators for changing climate and are important water reservoirs. The melt water from snow on glaciers and glacier ice is a major contributor to the runoff during the melting and the summer season and is thus supporting the water supply of the civilized regions downstream the rivers originating near Alpine glaciers. In the past, seasonal snow of the winter season remained throughout the year on the highest areas of glaciers building accumulation areas. In recent years the snow areas remaining at the end of the summer on the glaciers were significantly reduced. Additionally, on some of the glaciers in the Alps, the extent of debris covered glacier areas increased.

Different methods have been presented to estimate the snow line on glaciers at the end of the ablation season, and other approaches have been used to identify debris covered glacier areas. Most of these methods were demonstrated only for selected test sites and with limited data sets. In the frame of the ESA EXPRO+ AlpGlacier project (2021 – 2023), we developed an improved automated method for the identification of glacier facies, including snow areas, clean ice, and debris covered surfaces on glaciers from Sentinel-2 and Landsat data. The approach detects glacier facies for Alpine glaciers during the full melting period.

The processing chain starts with the automated download of level 1C (L1C) products from Sentinel-2 and Landsat with less than 30 % cloud cover. We tested and evaluated the performance of various cloud detection algorithms and products over glaciated areas available for Sentinel-2 and Landsat. We found that the s2cloudless and the CFMask show the best performance for Sentinel-2 and Landsat, respectively, and selected these methods for the cloud masking.

For the glacier facies classification, atmospherically and topographically corrected surface reflectance data are used. While detection of glacier facies on illuminated glacier areas is performing well, the correct classification in shaded areas is still a problem. We developed an advanced method for detecting shaded areas which is needed for topographic correction and estimation of surface reflectance in these areas. This procedure enables the identification of glacier facies also in cast shadowed glacier areas, where the classification from standard L1C top of atmosphere or L2A bottom of atmosphere reflectance data from Sentinel-2 and Landsat is limited due to low reflectances in all reflective spectral bands.

We will present the overall processing chain, highlighting the main improvements enabling an automated glacier facies classification, and show examples of the generated glacier facies products from Sentinel-2 and Landsat data for glaciers distributed over the Alps.

TanDEM-X Elevation Data For Mass Balance Estimation

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Ongoing global warming leads to dramatic changes in the cryosphere. In view of these rapid changes as well as the large uncertainties regarding forecasts, there is a constantly growing need for reliable and consistent information on the current state and the evolution of the ice sheets, ice caps and glaciers worldwide. In this context, satellite-based remote sensing allows cost-effective data collection even for inaccessible areas. Radar altimetry, gravimetry and laser altimetry have been widely used to detect height and mass changes. However, these systems either offer only point-based measurements or acquire at low spatial resolution. Since 2010, the single-pass SAR (Synthetic Aperture Radar) interferometry mission TanDEM-X provides area-wide information with high spatial resolution of 0.4 arcsec (i.e. about 12 m) at a global scale. The huge amount of globally consistent elevation data could contribute to meet the urgent need for information with high spatial resolution to monitor the dynamics of the cryosphere. However, the data suffers from an elevation bias up to several meters due to signal penetration. The penetration bias mainly depends on snow and ice characteristics as well as on the continuously changing acquisition geometry and underlies inter- and intra-annual variations. In this regard, we quantify the impact of X-band InSAR penetration bias on mass balance estimation based on TanDEM-X digital elevation models (DEM). In detail, a multiple regression model based on interferometric coherence and backscatter intensity is used to correct a time series of TanDEM-X DEMs acquired between 2010 and 2018 over the Devon Ice Cap (Nunavut, Canada), from which changes in elevation and mass are derived. For validation, GPS and laser altimeter measurements are used, which show good agreement between predictions and observations, with mean deviations between 0.1 and 0.5 m. The predictions well reflect the inter- and intra-annual variations, with a mean penetration bias varying between 2.5 and 4 m. Regarding mass balance estimation, corrected DEMs yield a 20% higher mass loss between 2010 and 2018 for the northwestern basin of the Devon ice cap compared to the uncorrected DEMs, with estimates based on the corrected data showing closer agreement with in situ mass balance measurements. Our results demonstrate the significant impact of X-band InSAR penetration bias on measurements of elevation change and mass loss and thus, the importance of correcting the TanDEM-X elevation data with respect to cryosphere and climate impact research.

Spatial Distribution and Decadal Change of Glaciers in the Indus Basin since the 1990s

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Stretching from the high mountains of the Hindu Kush-Karakoram range in the north to the dry alluvial plains of Pakistan in the south, the transboundary Indus River is the third longest river in the world. It is distributed across four countries: Afghanistan, China, India and Pakistan. We present a consistent, multidecadal glacier inventory of the Indus Basin for 1990, 2000, 2010, and 2020 based on a semi automated approach. Landsat Thematic Mapper (TM), Enhanced Thematic mapper (ETM+), and Operational Land Imager (OLI) imageries have been used ensuring minimum snow and cloud cover. Based on the Landsat images for 2020, a total of 19,797 glaciers encompassing a total area 23,622.40 km2 have been mapped in the Basin. There is a heterogeneous distribution of the glaciers across the basin with more than half i.e. 70 % of the total glacier area in the Upper Indus Basin, which only covers 33 % of the total area of Indus Basin. Within three decades (1990-2020), the glaciers in the Basin have experienced an overall reduction in their area by 6.4 % and in their number by 0.6 %. The Upper Indus sub basin has been found to have experienced the most pronounced depletion in glacier area than the other two sub basins, with an overall reduction in its area by 9.26 %. Strong spatial heterogeneity was observed in the glacier area changes in the basin which were influenced by surging and advancing glaciers. Using the buffer of half a pixel, we also evaluated the uncertainty of the glacier polygons, which resulted in an average mapping uncertainty of ±3.2%. These kind of regional multi-temporal glacier inventories are pivotal in setting the foundation stones for many machine learning approaches and also are very essential data for numerous glacio-hydrological and climate models.