SnowHydrology 2026

SnowHydrology 2026

5th International Conference on Snow Hydrology

Jaca (Spanish Pyrenees, Huesca)

2nd to 6th February 2026

Abstract Book

(ordered alphabetically by 1st author surname)

Authors: *Kristoffer Aalstad, Esteban Alonso-González, Joel Fiddes, Andreas Kääb, Norbert Pirk, Désirée Treichler, Sebastian Westermann, Stefan Wunderle, Yeliz Yilmaz*

Global ensemble-based mountain snow reanalysis

Snow is an essential climate variable that regulates the global cycles of energy, carbon, and water. However, the state of the snowpack is only partially observable by satellites due to gaps, noise, and indirect retrieval algorithms. The fusion of uncertain snow models and noisy observations through data assimilation presents a natural solution to this problem. Nonetheless, data assimilation has received relatively little attention from the snow remote sensing community despite its potential to serve as a generalized retrieval method that adds value by inferring gap-free hidden snow state variables with uncertainty quantification.

We present ongoing research on applying ensemble-based data assimilation techniques to produce a global mountain snow reanalysis constrained by satellite data. These efforts are motivated by the challenge of estimating seasonal snow mass in mountainous terrain which remains a major unsolved problem in snow hydrology. Taking a step towards solving this problem, we aim to generate the first global, consistent, ensemble-based, daily, kilometer-scale reanalysis of seasonal snow mass (i.e. snow water equivalent) and fractional snow-covered area dynamics for all mountains outside Antarctica.

To produce our reanalysis, we assimilate fractional snow-covered area satellite retrievals from ESA Snow_cci into a simple snow model run at a relatively high spatio-temporal resolution. Given the efficiency of our model, we are able to leverage promising iterative ensemble-based schemes while ensuring that the problem remains computationally feasible. Specifically, we build on developments hybridizing ensemble Kalman and particle methods for robust and tractable Bayesian inference. We also demonstrate how to hierarchically infer hyperparameters related to snow climatology. The new reanalysis approach is evaluated using independent spaceborne, airborne, and in-situ validation data. Finally, we benchmark the performance of our reanalysis by comparing it to other global mountain snow products.

Unlike existing global snow mass products, our product is uncertainty-aware and is tailored to address a key knowledge gap concerning mountain snow mass. We highlight that, by combining observations with models, data assimilation can transform largely untapped climate data into actionable climate information on essential climate variables. The uncertainty quantification in this probabilistic climate information enables informed decision making in response to climate change and its impacts.

Authors: *Johnmark Nyame Acheampong, Michal Jení?ek*

Snowmelt Controls on Seasonal Baseflow Fractions Across Mountains

Mountains act as crucial water towers, featuring steep terrain, seasonal snow-driven hydrology, and elevation-based climate zones that drive varied hydrological responses. Grasping the runoff mechanisms in mountain catchments is essential, particularly under climate change pressures. Snowmelt runoff overshadows liquid precipitation in these regions, making it highly susceptible to changes in snow accumulation and earlier melting periods. The relationship between snow and baseflow dynamics is vital for managing water availability across seasons and over multiple years. Yet, there remains uncertainty in linking snow conditions to baseflow across elevation gradients, as recent mesoscale studies have questioned traditional baseflow assumptions, highlighting the need for further research to clarify these interactions. This study tackles this gap by employing the HBV-light model across 88 catchments in Czechia and Swiss mountain regions from 1980 to 2020. Our results show elevation-driven patterns in baseflow generation, with higher annual and summer baseflow fractions during periods of increased snowfall. Snow water storage (SwS) serves as a key buffer in high-elevation catchments, extending baseflow recharge into late spring. We observed distinct time-lag effects between snowmelt and baseflow generation, varying by elevation, which leads to notable differences in seasonal flow dynamics between lower and higher elevation catchments. These findings enhance our understanding of mountain snow hydrology and provide critical insights for water resource management in snow-dominated regions facing growing climate challenges.

Authors: *B. Aguirre-Noguera, M. Bacardit, I. Moner, J. Gavaldà, E. Farías-Torbidoni, J. Revuelto, M. Pons*

Spatial Perception of Avalanche Hazard Based on Terrain Mapping and User Behavior Analysis

Terrain selection plays a key role in mitigating exposure to avalanche hazard and is therefore a critical factor to consider during winter mountain activities. This study aims to analyze the **spatial perception of avalanche hazard in high-mountain environments**, based on the available avalanche terrain mapping products.

First, we examine the **ATES 1.0 and ATES 2.0** terrain classification systems used in the Pyrenees, which integrate a range of topographic parameters to categorize terrain's avalanche exposure. Results indicate that **ATES 2.0 provides higher spatial resolution and detail**, enhancing decision-making for winter recreationists operating in avalanche terrain.

Subsequently, we assess the **understanding of the spatial distribution of avalanche hazard** among winter sports participants, using both the **Avalanche Bulletin** and the parameters incorporated in the ATES framework. The methodology combines mountain skier **surveys data and remote sensing techniques** to obtain complementary perspectives on how users perceive and interact with terrain under avalanche risk. The survey component evaluates the comprehension of mountain skiers and the use they do of the spatial information provided in the daily Avalanche Bulletin and the terrain parameters defined by the ATES matrix.

An experimental phase of the methodology was conducted in the **Swiss Alps** to test and validate the proposed analytical framework and instruments. This second pilot area also enable the assessment of **avalanche terrain mapping systems used in the Alps**, such as **ATHM** and **CAT**, allowing the integration of additional terrain parameters into the final methodological approach.

Overall, this research contributes to improving the understanding of how winter recreationists perceive and respond to avalanche terrain, supporting the development of more detailed spatial tools for avalanche risk management and decision-making in mountain environments.

Keywords: Avalanche hazard, terrain analysis, ATES, spatial perception, remote sensing, mountain safety, survey, Avalanche cartography

Authors: *Pertti Ala-aho, Harsh Beria, Shaakir Shabir Dar, Marius G. Floriancic, Aditya Mishra, Chandan Sarangi, Siyuan Wang*

Approaches to estimate snow partitioning to sublimation and melt fluxes across diverse environments in the CryoSCOPE project

The CryoSCOPE project aims to advance our understanding of cryosphere–atmosphere–hydrosphere (CAH) interactions by combining state-of-the-art in-situ observations and remotely sensed data. By improving process understanding and representation across spatiotemporal scales in Earth System Models, CryoSCOPE will generate new insights on how atmosphere constrains the changing cryosphere and how changes in the cryosphere affect ecosystem response, and deliver practical solutions to enhance resilience in sectors such as hydropower, forestry, and natural hazard mitigation.

Snow hydrology is a major focus in the CryoSCOPE project. We aim to develop integrated knowledge of the water budget in snow and ice dominated catchments by examining how CAH interactions affect meltwater generation at three representative sites (the Swiss Alps, the Finish Lapland and the Indian Himalaya). Using existing and establishing new in-situ and satellite observations, combined with the analyses of stable water isotope tracers, we quantify snow sublimation, and how meltwater is distributed between streamflow, groundwater, and evapotranspiration. These data will support the development of a coupled snow hydrology model at catchment scale across the diverse landscapes and climatic regimes of the Swiss Alps, the Finnish Lapland and the Indian Himalayas.

This presentation will describe the main ongoing and planned snow hydrology related field campaigns in the CryoSCOPE project. We focus on quantifying snow storage and melt fluxes in the diverse landscapes through continuous snow monitoring and dedicated sampling across sites. We will specifically focus on quantifying snow sublimation through Eddy Covariance methods combined with mixing models utilizing information from stable water isotope sampling campaigns. The field data will be used in isotope-aided hydrological modeling applications with the aim to simulate snow storage partitioning to sublimation and melt fluxes across the different landscapes.

Authors: *Konstantis Alexopoulos, Ian Willis, Hamish Pritchard, Giorgos Kyros, Vassiliki Kotroni and Kostas Lagouvardos*

snowMapper v1.0: an open-source model for reconstructing high-resolution daily snow cover over mountainous areas

snowMapper is a physics-informed, machine learning-driven model, designed for reconstructing daily snow cover over mountainous areas. It is trained on *in situ* observations, forced by gridded meteorological conditions, and assimilated with binary snow cover from high-resolution satellite imagery. It offers a modular structure that allows for case-specific configurations, returning reconstructed snow cover conditions at a daily timestep and in high spatial resolution, typically between 20-100 m. It features a preprocessing routine supporting satellite imagery from Landsat missions 4-9 and Sentinel-2; several filters for masking areas based on elevation, forest, water, urban and glacial-cover; five different configurable snow binarization schemes; and a MicroMet-based downscaling of auxiliary climate data. The reconstruction is performed by two successive and fully configurable gap-filling steps: a decision-tree algorithm followed by a machine learning classifier. Users can opt between training the machine learning classifier based on data from local *in situ* observations or, using observations from a different location disregarding the geographical coordinates. The result of the latter is a purely physics-informed classifier, optimal for regions with sparse or no *in situ* snow monitoring networks. An integrated validation scheme compares reconstructed results against satellite-derived observations, providing the accuracy of each model run in the final output. Optional temporal and spatial aggregation modules are also featured, enabling the calculation of spatiotemporal fractional snow cover. The entire process is performed using the cloud-based resources of Google Earth Engine through the Python API, minimizing the need for local sourcing of input datasets and eliminating local computational costs. The snowMapper model was used to reconstruct a 41-year snow cover climatology for Greek mountains exceeding 2,000 m a.s.l., where it demonstrated exceptionally high model skill. The model code and example data are available as an open-source project on GitHub (https://github.com/snowMapper/snowMapper, last access: 5 September 2025).

Authors: *Cecilia Almagioni, Davide Fugazza, Veronica Manara, Maurizio Maugeri*

Snow cover variability over the Italian territory: a focus on the Alps and Appennines chain from MODIS and AVHRR data

Snow cover plays an essential role in regulating the Earth's climate but it has significant impacts on human well-being in several parts of the world (e.g. source of freshwater for agriculture and human consumption, source of energy for hydroelectric power). In this study the spatial and temporal distribution of snow cover variables over the whole Italian territory which includes the southern part of the Alps and the Apennines chain between 2000 and 2025 using MODIS data acquired from Terra and Aqua platform are analyzed. After preprocessing the data to obtain a binary snow/no-snow field, the start (SOS), length (LOS), and end (EOS) of the snow season were calculated and analyzed.

The results reveal significant decreasing trends in the length of the snow season and in the other two metrics, particularly at higher elevations in both the Alps and the Apennines. To further investigate these patterns, AVHRR time series (1979–2023) were analyzed and compared with MODIS-derived metrics. The two datasets show good agreement over the overlapping period (2001–2023), suggesting that AVHRR data can be reliably used to extend the analysis to earlier decades and provide more robust long-term trends. Finally, both satellite-based datasets were compared with a modeled snow field derived from temperature and precipitation observations from Italian meteorological stations, providing a comprehensive picture of snow cover evolution over Italy in recent decades.

Authors: *Esteban Alonso-González, Adrian Harpold, Jessica D. Lundquist, Cara Piske, Laura Sourp, Kristoffer Aalstad, and Simon Gascoin*

Improving Snowpack Simulations in Forested Areas Using Ensemble-Based Data Assimilation

Snowpack dynamics controls hydrological and ecological processes across multiple spatio-temporal scales. Unfortunately, accurately monitoring the snowpack remains a significant challenge. Ensemble-based data assimilation offers a promising approach to reduce uncertainties in snowpack simulations by fusing physically-based models with observations. However, assimilating remotely sensed information in forest environments becomes complicated due to the limited visibility of the ground beneath the canopy.

In this study, we explore strategies for improving distributed snowpack simulations, from spatially incomplete observations through spatio-temporal data assimilation. Using the Multiple Snow data Assimilation system (MuSA), we explored the potential of different strategies of propagating the information obtained in forest clearings —where remotely sensed snow data can be retrieved— into sub-canopy areas that are typically not observable via remote sensing. We implemented different data assimilation experiments within the Sagehen Creek watershed (California, USA), assimilating airborne snow depth retrievals in forest gaps, using the sub-canopy retrieved information for validation.

Our results demonstrate great improvements in snowpack simulations, with correlation coefficients increasing from R = 0.1 to approximately R = 0.8, on average, with increased consistency with observed spatial patterns. We found that assimilation strategies based on geographical proximity and topographic similarity outperformed both the reference simulation without data assimilation and more complex approaches involving synthetic coordinate spaces derived from principal component analysis. Future efforts should focus on testing the method in different forest structures and climates, and on developing tailored localization functions that better capture spatial snowpack variability across heterogeneous forested landscapes.

Authors: *Juan A. Ballesteros-Cánovas*

Long-Term Snow Avalanche Dynamics in the Spanish Central Pyrenees

Snow avalanches are among the most significant natural hazards in mountain regions, and their frequency and magnitude are increasingly influenced by climate change. This study reconstructs avalanche activity over the last century in four avalanche paths located in Canfranc-Station, Los Arañones Valley (Central Spanish Pyrenees). To achieve this, we applied a multiproxy approach combining dendrochronology, geomorphological mapping, historical archives, and climatic data. Analysis of more than 500 trees reveals marked temporal variability: the largest avalanches occurred predominantly in the second half of the 20th century, whereas recent decades have been characterized by smaller but more frequent events, generally confined to upper slopes. Statistical analyses identify snowpack depth as the key mediator linking climatic drivers and avalanche occurrence, with negative phases of the North Atlantic Oscillation (NAO) associated with increased precipitation and lower temperatures, thereby enhancing avalanche probability. The study also explores the interaction between avalanche activity and protective infrastructure, focusing on how the performance and reliability of these structures have evolved over the last century. Our results highlight the importance of considering both natural and anthropogenic factors when analyzing long-term avalanche behavior, particularly in highly managed torrents. Overall, our findings underscore the non-linear response of avalanche regimes to climatic forcing and the threshold-dependent nature of snow-driven processes. These insights emphasize the value of integrating historical, ecological, and engineering data to improve risk assessment and support adaptive hazard management strategies in alpine environments undergoing rapid cryospheric change.

Authors: *Javier Bandrés, Josep Bonsoms, Jorge Pey, Pablo Domínguez-Aguilar, Jesús Revuelto, Eñaut Izagirre, Francisco Rojas-Heredia and Juan Ignacio López-Moreno*

Integrating field observations and snowpack modelling to assess snow impurity effects in the Central Pyrenees

Aerosols and light-absorbing impurities (LAIs), such as African dust and black carbon, significantly impact snowpack dynamics when deposited on the surface, as they reduce snow albedo, alter the energy balance, and accelerate snowmelt. Snowpacks in mountain ranges such as the Pyrenees are frequently affected by dust deposition events originating from North African deserts, which contribute more than half of the annual dust load over the range. African dust air masses reach the Pyrenees approximately 15% of the days each year, with a clear increasing trend observed in recent decades. The mountain range acts as a natural barrier that enhances the atmospheric cleansing of pollutants, trapping African dust on the southern slopes and pollutants from northern sources on the northern slopes, through Foehn-related effect.

However, the scarcity of in-situ measurements has limited our ability to quantify these effects and to accurately constrain snowpack models. LAIs in the snow are often not included in future glacier and snow simulations, despite their important influence on snow structure, hydrological availability, and other processes.

For this work, field observational data such as surface albedo measurements at the Izas catchment (Central Spanish Pyrenees) and chemical analyses of black carbon and African dust concentrations from snow samples were combined with meteorological forcing data from the SAFRAN reanalysis. These measurements were key to quantifying albedo decay during periods of high dust concentration. The multilayer, physically based snow model SNOWPACK was validated and applied to a set of numerical experiments comparing scenarios with high, average, and observed albedo values caused by impurity deposition. This approach allowed investigation of impurity impacts both within a single season and across consecutive years.

Results show that the deposition of LAIs leads to an earlier onset of snowmelt and substantially increases melt rates during deposition events compared with average albedo conditions, and even more markedly compared with clean-snow scenarios. These findings are consistent with previous observations at Izas and highlight the strong and rapid response of snowmelt timing and magnitude to impurity-induced albedo changes.

Authors: *Javier Bandrés, Jorge Pey, Jesús Revuelto, Eñaut Izagirre, Esteban Alonso?González, Pablo Domínguez-Aguilar and Juan Ignacio López-Moreno*

Snowmelt enhancement by light-absorbing impurities: observational and modelling insights from the Spanish Central Pyrenees

Snowpacks in mid-latitude mountain ranges are strongly affected by both climatic variability and atmospheric deposition processes. In last years, African dust outbreaks are becoming more frequent and intense, while emissions of black carbon are gradually declining across Europe. This context controls the amount and the composition of light-absorbing impurities (LAIs) deposited on the snow surface. These particles reduce snow albedo, enhance the absorption of solar radiation, and accelerate snowmelt. However, quantitative assessments that combine in situ observations with physically based snowpack modelling remain scarce for this region.

In this study, we evaluate the impact of LAIs deposition on snow cover evolution in a catchment of the Spanish Central Pyrenees. Field observations included meteorological and snowpack data collected from an automatic weather station, along with albedo measurements, snow sampling, liquid water content (LWC), specific surface area (SSA), and impurity concentration using aerosol deposition instrumentation. These datasets provide the basis to compare increases in snowmelt rates under different environmental conditions and with a snowpack affected by varying ranges of deposited impurities.

In addition, we performed simulations with FSM2 that includes a radiative transfer scheme. Two scenarios were considered: (1) a reference run without LAI forcing and (2) a LAI-forced run using deposition estimates derived from reanalysis products together with available in situ measurements. This structure allows a direct comparison of snowpack dynamics under clean and impurity-affected conditions.

By combining field measurements with process-based modelling, this work provides a robust quantification of the radiative and hydrological impacts of African dust deposition on Pyrenean snow.

Authors: *Emmanuelle Barrette, Vincent Vionnet, Benjamin Bouchard and Daniel F. Nadeau*

Tree sway monitoring for improved parametrization of canopy snow interception in cold, wet climates

Snow is an essential component of the hydrological cycle in cold regions. In forested areas, snow interception by the canopy modulates snow accumulation on the ground and affects surface albedo, which indirectly influences net radiation balance, surface temperature and heat exchange. Sublimation of intercepted snow also returns moisture to the atmosphere. Given the extent of forested landscapes across cold and wet climates, accurate representation of this process is crucial in climate, meteorological, and hydrological models. However, snow interception remains poorly documented in the field, especially in cold, wet continental climates such as those found in eastern Canada.

The objective of this research project is to analyze snow interception by the forest canopy in eastern Canada using innovative experimental measurements and to improve the parametrization of canopy interception used in the SVS2-Crocus land surface model.

Snow interception is monitored on nine trees (balsam firs, white spruces, and black spruces) from three study sites: Laval University Campus (46.8°N, 71.3°W), Montmorency Forest (47.3°N, 71.1°W), and Romaine River valley (51°N, 63°W). Hourly timelapse photography provides qualitative observations of interception. Quantitative estimations of snow interception at tree level are obtained using accelerometers to monitor wind-induced tree sway and to correlate changes in sway frequency with variations in intercepted snow mass. Because sway frequency is strongly influenced by temperature, we first establish a relationship between air temperature and the natural frequency of each tree under snow-free conditions. This step removes the thermal effect on wood rigidity, isolating the signal associated with snow loading. Each tree is calibrated with known weights and manual swaying to establish the sway-mass relationship, allowing for estimation of intercepted snow mass from accelerometer data. Preliminary results from winter 2024/25 show concordance between sway-based snow estimates and timelapse observations. The sway method captured rapid loading and unloading, with frequency responding to interception and release within a few hours. At the Romaine site, intercepted snow was confirmed in 20% of daytime images for one black spruce between November 8th and May 8th, while 52% of accelerometer data provided a sufficiently strong signal to determine sway frequency. This approach enables the construction of hourly time series of intercepted snow. Measurements of temperature, humidity, radiation, pressure, wind speed and precipitation are collected to link interception dynamics to meteorological conditions. The resulting dataset is used to drive and evaluate the parametrization of canopy interception in the SVS2-Crocus land surface model used by Environment and Climate Change Canada.

Authors: *Basile de Fleurian, Patrick Leibersperger, Kevin Fourteau, Lisa Bouvet, Neige Calonne, Matthieu Lafaysse, Mathias Bavay, Michael Lehning and Marie Dumont*

Evaluation of the thermal core of the Helmut Snowpack model.

Modelling of snowpack evolution is key for a number of applications ranging from the forecasting of avalanches to the prediction of future runoff or the impact of snow cover variations on future climates. Thermal conditions are one of the main driver in the evolution of the snowpack, driving most of the other processes at play in the snowpack. Hence the core of physiscal snow models should be a reliable, robust and verified heat exchange solver.

We present here Helmut, a new snowpack evolution model developed as part of the IVORI program (https://ivori.osug.fr/). The model is designed to be modular, easy to develop and easy to couple and could be used for natural snowpack modelling but also to explore different formulations of the processes at play in order to optimise operational models.

To evaluate this new model we perform simulations with Helmut to reproduce controlled cold room experiments (Bouvet et al. 2023). Under a prescribed temperature gradient and with a controlled snow volume we evaluate the temporal evolution of the simulated snow temperature. We also compare the simulated snow SSA with the one derived from the tomographies performed during the experiments.

Bouvet et al. :Bouvet, L. and Calonne, N. and Flin, F. and Geindreau, C., Heterogeneous grain growth and vertical mass transfer within a snow layer under a temperature gradient. The Cryosphere, 2023, doi:10.5194/tc-17-3553-2023

Authors: *Ezra Beernaert, Jaron Vandenbroucke, Kari Luojus and Hans Lievens*

Towards High-Resolution Snow Water Equivalent Estimates at Global Scale Based on Satellite Data Assimilation

Observations of snow water equivalent (SWE) in the world's mountain ranges remain scarce, hindering accurate estimates of total seasonal water storage. To address this gap, we implemented a physical snow model and satellite data assimilation system, to obtain daily snow depth (SD) and SWE estimates for large regions.

To generate a high-resolution SWE dataset, high-resolution meteorological forcings are required. We used the Multi-Source Weather (MSWX) and Multi-Source Weighted-Ensemble Precipitation (MSWEP) datasets, which provide globally available 3-hourly forcings at 0.1° resolution. These inputs were downscaled to a resolution of 500 meter to account for terrain influences. Different options for the downscaling procedures (with the main focus on precipitation, temperature and solar radiation) were explored and evaluated to select the combination of methods that produced the most accurate SD and SWE simulations. A physically based snow model (SnowClim, developed by Lute et al., 2022) was calibrated to optimize performance.

Further improvements are achieved through data assimilation. Sentinel-1 SD retrievals (Lievens et al., 2019, 2022) are assimilated in mountainous regions, while in non-mountainous regions of the Northern Hemisphere, the GlobSnow SWE dataset (Luojus, K., Pulliainen, J., Takala, M. et al., 2021) is available. In Europe, the FMI-HSAF super resolution SWE (Takala, M. et al. 2016), which has a higher resolution than GlobSnow, is assimilated. Over the European Alps, assimilation of Sentinel-1 SD retrievals improved estimates of both SD and SWE compared to model or satellite products alone. Extending to Northern Europe (Norway, Sweden, Finland), the combined assimilation of Sentinel-1 and FMI-HSAF super resolution SWE clearly demonstrated the advantage of integrating satellite information with a physical snow model for high-resolution, spatially distributed SWE estimation.

Building on the demonstrated improvements for high-resolution SWE estimates in Europe, the approach provides a strong basis for extending the framework towards other regions. First, implementation over the Rocky Mountains will help strengthen the system, as long-term in-situ datasets as well as LiDAR observations from the Airborne Snow Observatory (ASO) enable additional opportunities for spatial performance assessment. In parallel, adapting the system for the Southern Hemisphere, where reversed seasonality and lack of extensive in-situ datasets pose unique challenges, will be an important step. Together, these efforts support the development of a robust, globally consistent SWE product that can have broad impacts for water resource management and climate applications.

Authors: *Víctor Berdejo-Arceiz, Víctor Herraiz-López, Borja Latorre, Ayla Marzo-Lorente, Leticia Gaspar, Adrián Subías Martín, Samuel T. Buisan and Rafael Alonso*

Design and Field Implementation of an Open and Low-Cost Gamma-Ray Device for SWE and Environmental Monitoring

The snow water equivalent (SWE) is the most important hydrological variable of the snowpack. Different measurement technologies can be used its continuous and remote monitoring. For example, SWE measurements can be performed by measuring the attenuation and time delay of the global navigation satellite system (GNSS) signals, the attenuation under the snowpack of neutrons generated by cosmic rays in the atmosphere, or the attenuation of the natural gamma radiation generated by the soil under the snowpack. Gamma-ray spectroscopy is not a common technology, as sensors usually require complex, large, and expensive gamma detectors. However, recent advances in low-cost gamma spectrometers can allow the design of portable and cost-effective gamma detectors, solving some of the problems of the SWE sensors based on gamma-ray spectroscopy.

In this work, we present the feasibility of employing portable low-cost gamma-ray spectrometers for measuring the SWE using the natural gamma radiation generated by the soil under the snowpack. We present the open hardware all-in-one device gamma-ray spectrometer employed, the Open Gamma Detector, and the energy and thermal calibration performed to be able to use it under environmental conditions during winter.

We also present the results of the continuous operation of the sensor during the 2024-2025 winter season at the AEMET-Formigal-Sarrios test site, located in the Spanish Pyrenees at an elevation of 1800 meters above sea level. We show how the sensor allows monitoring events such as SWE increments during snowfalls and decrements during the melting period. Furthermore, the sensor also allows the detection of small snowfalls and rain-on-snow events which are difficult to detect based on conventional SWE measurement techniques.

Additionally, once the snow has melted, we observed a correlation between soil moisture and the detected signal, as well as the detection of rainfall events, thereby enabling its use as a multipurpose environmental monitoring device.

These results demonstrate that low-cost gamma-ray spectroscopy can potentially be a cost-effective and reliable technology for SWE monitoring under different environmental and snowpack conditions, opening the path to cost-effective snow hydrology networks. Hydrological forecasting of snow-covered areas and downstream regions could be significantly improved by the deployment of a portable and cost-effective SWE measurement device based on gamma-ray spectroscopy, complementing the already widespread technologies.

Authors: *Harsh Beria, Lionel Benoit, Natalie Ceperley, Bettina Schaefli*

Advancing snow hydrology through stable water isotopes: insights from isotope-enabled modeling of hydrological partitioning in the Swiss Alps

Traditional rainfall-runoff models are typically calibrated against streamflow at a catchment outlet alone, which often fails to adequately constrain the underlying hydrological processes within a catchment, especially in snow-dominated alpine environments. Incorporating naturally occurring conservative tracers such as stable water isotopes allow tracking precipitation as it is stored and released by the catchment, before eventually reaching the stream outlet. Stable water isotopes can therefore provide additional constraints on model structure, promising improved model reliability. To date, stable water isotopes have been used qualitatively to refine model structure and quantitatively to calibrate complex solute transport models, requiring more parameters. There has been limited work on implementing particle tracking routines within conceptual hydrological models.

Here, we present a novel particle tracking routine integrated into an existing hydrological model based on the Geomorphological Instantaneous Unit Hydrograph and multiple groundwater reservoirs. The model simulates streamflow and streamflow isotopes at high temporal resolution (10-minute intervals) in a headwater catchment in the Swiss Alps (Vallon de Nant). By jointly calibrating the model with streamflow and streamflow isotopes, we show reduced parameter uncertainty and altered flux partitioning, with higher snowmelt contribution to streamflow routed through groundwater. Despite the catchment's high flashiness, where peak streamflow occurs within an hour of peak rainfall, most streamflow originates from groundwater. This can be effectively represented by two subsurface storages and parameterized with nonlinear storage-discharge relationships.

Our results highlight the benefits of incorporating stable water isotopes in hydrological modeling to both refine model structure and reduce parameter uncertainty. We also discuss the advantages and limitations of the proposed isotope-enabled modeling approach and its potential extension to other catchments.

Authors: *Giacomo Bertoldi[1], Michele Bozzoli[1], Valentina Premier[1], Carlo Marin[1], Emanuele Cordano[2], Giuseppe Formetta3, John Mohd Wani3, Matteo Dall' Amico4, Federico Di Paolo4, Stefano Tasin4 Affiliations: [1]EURAC Research, Bolzano, Italy [2]Rendena100, Tione di Trento, Italy 3University of Trento, Italy 4Waterjade Srl, Trento, Italy*

Comparative Evaluation of Three Approaches for SWE and Runoff Modeling in Mountain Catchments: Insights from the SnowTinel Project

Accurate modeling of Snow Water Equivalent (SWE) and runoff in alpine catchments remains a critical challenge for hydrological forecasting and water resource management. Within the framework of the SnowTinel project, we present a comparative evaluation of three distinct approaches for modeling SWE and discharge in mountain catchments, with a focus on their predictive accuracy, operational complexity, and computational efficiency.

The first approach employs the fully distributed GEOtop model to simulate SWE and snowmelt processes. These outputs are then assimilated into the semi-distributed GEOframe model, allowing for a hybrid modeling strategy that leverages GEOtop's spatial resolution and GEOframe's hydrological robustness.

The second approach extends the first by incorporating data assimilation of snow depth observations from automatic stations as "virtual meteorological stations" and MODIS-derived Snow Covered Area (SCA) maps. This enhanced assimilation improves the accuracy of snow accumulation and melt estimates, and better captures the spatial extent of snow cover.

The third approach combines daily SCA maps from multi-source optical data with the GEOframe model to reconstruct SWE at high-spatial resolution. This method builds on previous work and demonstrates the potential of combining hydrological modeling with spatially enhanced snow cover information. Preliminary results indicate that the machine learning-enhanced GEOframe approach offers simplicity and good spatial accuracy, although it requires snow depth observations and accurate discharge observations. Physical modelling methods provide acceptable results even when ground observations are limited. Assimilation-based methods offer superior spatial accuracy, especially when snow depth observational data are integrated, but they require longer computational time and a more complex operational workflow. This comparative study highlights the trade-offs between model sophistication and operational practicality, offering valuable insights for future implementations of snow hydrology models in alpine regions.

Authors: *Diego Blanch, James McPhee, Maria Courard, Carlo Marin, Valentina Premier, Riccardo Barella*

Exploring the value of Sentinel-1 data for improving snowpack simulations in the Mediterranean Andes Cordillera

The seasonal snowpack of the mediterranean Andes of Chile holds a critical role in supplying water for agriculture, ecosystems, industries and drinking water for up to eight million in the city of Santiago alone. Despite the above, its characterization remains highly uncertain due to the scarcity of in-situ observations and the complex topography of the region. In this context, physically based snow models provide an opportunity to produce high resolution estimates of the main snowpack variables: snow water equivalent (SWE) and snow depth (SD). However, from recent modeling efforts in this mountain range, the performance of these simulations is hampered mostly by uncertainty in precipitation amounts, which are currently not well resolved by global reanalysis datasets nor by station-based gridded products.

This study aims to address the forcing uncertainty problem and enhance snowpack simulations by assimilating Sentinel-1 C-band synthetic aperture radar (SAR)-derived snow depth and wet snow retrievals. These observations are assimilated into the Canadian Hydrological Model, a variable resolution, physically based snowpack modeling platform. The study domain comprises two high mountain basins of about 600 square kilometres located in the Chilean Andes, within latitudes 33-34 degrees South.

To assess the value of the Sentinel-1 data, we conduct a control experiment where only snow-covered area (SCA) is assimilated. Then, we carry out the assimilation of snow depths and wet snow maps. Finally, the assimilation experiment using Sentinel-1 products is compared to the control (SCA only) through evaluation against ground truth data (terrestrial LiDAR, Pléiades retrievals and station measurements of SWE and SD). This allows to answer whether these new sources of snowpack information constitute an improvement over the more traditional SCA assimilation, or if more work is needed to make these Sentinel-1 products usable in data assimilation over the Andes. The combination of continuous, all-condition remote sensing data like C-band SAR and a high-resolution snow model could be a step forward in water resources monitoring, particularly in data scarce regions like the Andes Cordillera

Authors: *Elias Bögl, Sergi Gonzàlez-Herrero, Michael Lehning, Korbinian Achmüller, Christian Voigt, Karsten Schulz and Franziska Koch*

Estimating sublimation in complex alpine terrain with a combined modelling and monitoring approach including superconducting gravimetry

The accurate model representation of boundary layer fluxes in high alpine terrain is challenging due to a sparse database, complex turbulence driven interaction of surface and atmospheric layers and computational demand. A superconducting gravimeter (SG) installed in the high-alpine, snow-driven area of Mt. Zugspitze, Germany, enables the first gravity-based evaluation of cryospheric and snow-hydrological models at scales of up to 40 km². The integral spatio-temporal changes of the cryo-hydrological mass effect on the gravitational field are captured on a minute temporal resolution with a sensitivity to uniform snowpack alterations of ?1-2 mm SWE leading to ?1 nm/s2. The in-situ measurements of an Eddy-Covariance (EC) station and a particle counting (SPC) sensor allows to identify and differentiate cases of surface and drifting/blowing snow sublimation events. The physically-based model SNOWPACK/Alpine3D provides a spatio-temporal snow cover simulation on a 16 m grid resolution. It is forced with redistributed precipitation based on satellite derived snow height map and meteorological station data. A multilevel validation of the simulation is conducted via continuous snow height and mass point measurements, the routed flux of a hydrological model against discharge observations, snow-covered area information from satellite and cryo-hydrological residuals of the integral signal of the superconducting gravimeter. For distinct periods of surface and blowing/drifting snow sublimation in the last two years (2024-2025), the snow-atmospheric coupled model CRYOWRF is applied. It simulates with SNOWPACK the dynamics of a large number of layers governed by snow layer grain-scale prognostic variables with online coupling to the atmosphere for multiscale simulations from the synoptic to the turbulent scales and contains a blowing snow scheme. With the entire modelling and monitoring setup we aim to disentangle the physical processes of surface and blowing snow sublimation as well as wind -induced redistribution. The coupled model CRYOWRF and the standalone Alpine3D simulations are evaluated using gravitational data and in-situ measured EC and SPC data. Our first results provide valuable insights into process representations on a km-scale area in complex alpine terrain.

Authors: *Érika Boisvert-Vigneault, Melody Sandells, Nick Rutter, Vincent Vionnet, Alexandre Langlois, Hannah Bloom,*

Modelling Major Arctic Rain-on-Snow Events with Snow Model Crocus-SVS2

Rain-on-snow (ROS) events are an increasingly prevalent Arctic extreme weather phenomenon, driven by accelerated atmospheric warming. These events create ice layers within the snowpack, which can prevent foraging for ungulates like reindeers, caribou and muskoxen and have been linked to catastrophic herd die-offs. Accurately simulating the physical consequences of ROS, specifically the development of these ice crusts, is therefore critical for assessing wildlife habitat suitability. However, the performance of detailed snow models in high-latitude environments remains inadequately evaluated, particularly their ability to replicate the snowpack stratigraphy following complex meteorological events.

This study investigates the capacity of the snow model Crocus-SVS2 to simulate the impacts of known, major ROS events on the snowpack of Banks Island, Nunavut. We focus on a case study where a documented ROS event was followed by a severe muskoxen mortality event in the winter of 2003-2004. Our methodology forces the Crocus-SVS2 model with three distinct meteorological reanalysis datasets: the Regional Deterministic Prediction System (RDRS v2.1), the Canadian Surface Reanalysis (CaSR3.1), and the ERA5 reanalysis. This multi-forcing approach allows to assess not only the model's physical fidelity but also the sensitivity of the simulations to different weather inputs, thereby evaluating the ability of reanalysis products to represent ROS in the Arctic accurately.

Model outputs are analysed to determine if Crocus-SVS2 can successfully replicate the formation, thickness, and vertical position of observed ice lenses within the snow profile. The primary outcome is a robust evaluation of whether current snow model, when driven by the best available meteorological data, can serve as a reliable tool for retrospectively analysing ROS impacts in data-sparse Arctic regions. This research also provides a framework to identify the key meteorological conditions that separate minor ROS events from those causing catastrophic ungulate die-offs.

Authors: *Josep Bonsoms, Sergi González, Xavier Fettweis, Marc Lemus-Cánovas, Marc Oliva, Juan I. López-Moreno*

Attributing Greenland Ice Sheet Extreme Melt Events to Climate Change

The Greenland Ice Sheet (GrIS) has experienced a marked intensification of summer surface melting, with extreme melt events becoming increasingly frequent, extensive, and severe. Despite its central role in global sea-level rise and downstream hydrology, formal attribution of these extreme events remains limited. Here, we present the first attribution analysis of the top 10 extreme melt events on the GrIS (1950–2023), disentangling thermodynamic (warming-driven processes) and dynamic (atmospheric circulation-driven processes) contributions using a novel flow-analogue framework coupled with meltwater outputs from the regional climate model MAR v3.14 and validated against satellite-derived melt products. Extreme melt events are defined as days when detrended meltwater production exceeds the 95th percentile, allowing robust isolation from underlying trends.

Our results indicate that thermodynamic contributions and meltwater spatial expansion amplify meltwater production by roughly 25–30% relative to pre-1975 extreme melt analogues. Northern Greenland, particularly the NE and NW sectors, exhibits the strongest intensification, with some events exceeding historical analogues by more than 300%. Since 2000, seven of the top 10 extreme events have been recorded, highlighting the emergence of unprecedented melt conditions. Future projections under high-emissions scenarios (RCP8.5 and SSP5-8.5) suggest that extreme meltwater anomalies could increase by up to 350–370% by 2100, with northern Greenland remaining a persistent hotspot.

This study demonstrates that extreme summer melt events on the GrIS are no longer rare anomalies but are now recurring features of the modern melt season, driven primarily by anthropogenic climate change. These findings provide an improved understanding of Greenland's mass balance, regional hydrology, and downstream impacts on the North Atlantic climate system and mid-latitude weather patterns.

Authors: *Kat J. Bormann, Cara R. Piske, Jeff S. Deems, Thomas H. Painter*

Airborne Snow Observatories - high-accuracy depth, SWE, and albedo mapping for 4-D snowpack monitoring

Airborne Snow Observatories (ASO) snow depth and SWE products have, over time, become the benchmark for spatially distributed snow data. Quantification of the accuracy and precision of remote sensed and other spatially distributed SWE products, particularly those used as validation sources such as ASO, is important for their interpretation and provides crucial guidance for end users as to how these products are used. We evaluated ASO snow depth retrievals and bias-adjusted bulk snow density estimates from a physically based snow model with in-situ observations in the Western US from our 2024 and 2025 operational seasons. Providing over 650 comparisons with our 3m snow depth product spanning both the accumulation and melting season. We also compare snow albedo retrievals with coincident satellite observations. We found that our snow depth accuracy is better than the previously reported 8 cm (Painter et al., 2016) and observed unbiased snow density estimates over time. The accuracy of ASO's snow products was consistent across time and space and are not perturbed by liquid water presence or snow microphysics. For water management purposes, the ASO spatially distributed SWE data can be aggregated into basin SWE total volumes that are highly correlated with streamflow runoff in snow dominated watersheds. Due to the accuracy of the individual components (snow depth and bulk density estimates), the total SWE volumes at the watershed scale are also highly accurate with low interannual errors; and as such can provide great confidence when used for water management decision making.

Authors: *Lisa Bouvet, Kévin Fourteau, Neige Calonne, Marie Dumont, Laurent Arnaud, Oscar Dick, Mathieu Fructus, Pascal Hagenmuller, Daniel Kramer, Alexandre Langlois, Yves Lejeune, Julien Meloche, Jacques Roulle, Arvids Silis, Louis Védrine, Vincent Vionnet*

Water vapor transport: the missing piece to better describe the Arctic snowpack?

The tundra snowpack covers a large portion of the Earth's surface and is subject to unique environmental conditions, with thin snowpacks undergoing high-temperature gradients and exposed to high winds. These conditions lead to specific evolution of the snow stratigraphy, often simplified in a bilayer snowpack composed of a top high-density wind slab, and a bottom low-density depth hoar layer.

The processes leading to the formation of such snowpacks are ongoing research questions and involve wind effects, heat and water vapor transport. One widespread hypothesis is that water vapor diffusion induced by the strong vertical temperature gradient dries out the bottom half of the snowpack (the depth hoar layer), which would then gradually lose density during the winter. Recent studies have therefore focused on the challenging implementation of water vapor transport in snow models with the expectation of predicting the low density of the bottom layer.

Here we discuss this hypothesis, based on observations from a new dataset of an eight-month-long field campaign (IVORI) which was conducted in Cambridge Bay at the Canadian High Arctic Research Station, Nunavut, Canada (69°N) during the 2023-2024 winter. From high resolution density profile monitoring, we explore alternative hypotheses for the formation of the low-density bottom layer. This layer could for instance originate from fresh snow rapidly transformed into depth hoar without gaining density rather than the de-densification of initially denser snow. The role of the upper wind slab and vegetation will also be addressed.

Authors: *Samuel Buisan, Craig Smith, Michael Earle, Yves-Alain Roulet, Mareile Wolff and Isabelle Ruedi*

An update of WMO best practices for precipitation measurements

One of the main inputs for hydrological services is precipitation amount, and an accurate measurement of this variable is crucial for any other related applications. Complexity of the measurement increases substantially when the precipitation is solid (i.e. snow).

This work presents a recently published (2025) update of Chapter 6 (Measurement of precipitation) in Volume I of the Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8). The update, and the associated new recommendations on best practices for precipitation measurement, focuses on automated and solid precipitation measurements, and are based on results from the WMO Solid Precipitation Inter-Comparison Experiment (SPICE) and related literature. The updates proposed for automated measurement guidelines are a full set of new recommendations on topics that were not included in previous versions of the guide

New topics include the use of oil and antifreeze and how to mitigate the problem of snow capping by heating instruments. A significant addition is best practices on how to apply transfer functions to precipitation observations to adjust for wind-induced error, which plays a critical role in the measurement of solid precipitation. Recommendations on how to perform quality control of automated observations and on the requirements of an intercomparison site are also presented. A compilation and update of existing measurement procedures to reflect current and new technologies and associated recommendations are included. New images, drawings and diagrams have been incorporated to illustrate the real challenges for precipitation measurement.

This major update of Chapter 6, Vol. 1 of WMO No. 8 ensures comprehensive and uniform information on state-of-the-art best practices for precipitation measurement, that are widely accessible and useable by the measurement community.

The snow hydrology community can benefit from these recommendations for the development of robust and consistent methods of observation.

Authors: *Samuel Buisan, Jorge Monforte, José Luís Collado*

Intercomparison of SWE measurements with snowpack model and true snow precipitation

Spanish State Meteorological Agency (AEMET) Formigal–Sarrios test site is located in the Spanish Pyrenees (42°45'40.6"N 0°23'31.8"W) at an elevation of 1800 m a.s.l. Currently, the site is equipped with sensors to continuously record meteorological and snow properties. The site also include a reference for solid precipitation, a Double Fence Automated Reference (DFAR), laser snow depth sensors and also a Cosmic ray neutron sensor (CRNS) from the Ebro basin hydrological service to estimate snow water equivalent (SWE).

SNOWPACK model developed by Swiss Institute for Snow and Avalanche Research is running in Formigal since 2022-2023 winter season.

An intercomparison of snowpack model, SWE measurements and true precipitation from DFAR for 3 winter seasons is presented

The main objective of this work is to assess the performance of Snowpack model with experimental measurements and to identify under which meteorological and snow conditions the agreement is better or worse

Authors: *Tomàs Cardona-Sastre, Esteban Alonso-González, Kristoffer Aalstad, Simon Filhol, Adrián Melón-Nava, Javier Santos-González, Andrés Merino Suances*

Snow Data assimilation using Sentinel-2 for the Cantabrian Mountains (Northern Iberia)

Knowledge of snowpack conditions and its distribution is key to understanding the evolution of water resources and ecological processes in mountain regions. However, direct snowpack observations in these regions are scarce, raising the need to produce datasets based on snowpack numerical simulations. Unfortunately, these simulations are affected by uncertainties in the forcing meteorological data and suffer from the challenges of simulating the snowpack spatial variability, induced by wind redistribution and preferential deposition. Snow cover observations from space offer global coverage at high resolution (tens of meters) but are limited by 1) the satellite revisit frequency, 2) the geometry between the sun the satellite and the topography geometry, 3) the possible presence of clouds and 4) the uncertainties in the algorithm retrieving snow cover from satellite imagery.

This work presents a spatially and temporally enhanced snowpack dataset for the Picos de Europa National Park (NW Spain). We have used the TopoPyScale toolbox to downscale the reanalysis dataset ERA5 to generate 60m meteorological forcing for the period 2016-2025. We have used this downscaled data as a forcing for the Multiple Snow Data Assimilation system (MuSA) which assimilates Sentinel-2 fractional snow-covered area (fSCA) from the Copernicus Land Monitoring System observations into an ensemble of simulations generated by the Flexible Snow Model (FSM2.0) multi-physics energy balance model. To address the computational challenge while avoiding ensemble collapse, we have used a new iterative algorithm: the Adaptive Particle Batch Smoother (AdaPBS) scheme. The result is a high-resolution (3 hour timesteps and 60 meter resolution) dataset of snow depth and snow water equivalent for the 2016–2024 period (hydrological years) validated with snow cover time-lapsed imagery.

Authors: *Francesca Carletti, Carlo Marin, Chiara Ghielmini, Riccardo Barella, Mathias Bavay, Michael Lehning*

The role of liquid water and surface roughness on the multitemporal Sentinel-1 backscatter during snowmelt: from high-resolution field measurements to radiative transfer modelling

The spatiotemporal evolution of snow melt is fundamental for water resources management and risk mitigation in mountain catchments. Synthetic Aperture Radar (SAR) images acquired by satellite systems such as Sentinel-1 (S1) are promising for monitoring wet snow due to their high sensitivity to liquid water content (LWC) and ability to provide spatially distributed data at a high temporal resolution. While recent studies have linked S1 backscatter to different melting phases, a correlation with detailed snowpack properties is still missing. To bridge the gap, we collected the first dataset of detailed wet snow properties tailored for SAR applications over two consecutive snow seasons at the Weissfluhjoch field site in Switzerland.

We used our measurements as input to the Snow Microwave Radiative Transfer (SMRT) model to simulate S1 backscatter signals. Our results indicate that rather than capturing distinct melting phases, backscatter time series reflect two main regimes: one dominated by LWC, early in the season, and another by surface roughness, later on. The early-season, LWC-dominated period likely represents the only viable window for data assimilation in snow hydrology applications.

These findings highlight important challenges in reconciling S1 signals with radiative transfer simulations of wet snow, including (i) the discrepancy between point-scale LWC measurements and its spatiotemporal variability likely observed by satellites, and (ii) the absence of fully validated models describing the permittivity, the microstructure and surface roughness of wet snow in the C-band. At the same time, our results suggest that point-scale measurements potentially don't capture wet snow features which generate strong scattering effects on larger scales, such as surface roughness. Thus, understanding the evolution and drivers of surface roughness becomes essential for developing meteorologically based parameterizations to interpret multitemporal backscatter for snow hydrology applications.

Authors: *Carlo Marin, James McPhee, Valentina Premier, Riccardo Barella, Diego Blanch, Paloma Palma, Ezequiel Toum, Jeroen Dries, Patrick Henkel, Markus Lamm, James Thornton, Mariano Masiokas*

A 20-Year, 50-meter Reanalysis Dataset of Snow Water Equivalent and Ice Melt for the extra-tropical Andes

Snow and glacier meltwater are vital for sustaining drinking water, agriculture, hydropower, and industry in mountain regions, yet their monitoring remains limited—particularly in the extra-tropical Andes, where millions depend on meltwater resources. Climate change further amplifies the need for reliable quantification to support hydrological forecasting and water management. The Horizon Europe project SNOWCOP addresses this challenge by delivering a novel, high-resolution (50 m, daily) reanalysis of snow water equivalent (SWE) and ice melt rates spanning more than 20 years.

SNOWCOP integrates multi-source remote sensing, downscaled re-analysis atmospheric data, and physically based modelling within a modular workflow. Copernicus and third-party satellite observations (Sentinel-1, Sentinel-2, MODIS, Landsat, VIIRS) are exploited. Snow cover area is reconstructed by fusing high-resolution optical imagery with daily lower-resolution snow cover fraction, while meteorological inputs are downscaled from ERA5-Land. SWE is estimated with retrospective reconstruction methods that explore three different levels of complexity: energy balance, temperature index, and enhanced temperature index models. Calibration and evaluation rely on independent in situ measurements and field campaigns, including terrestrial lidar scanning and snow density surveys, respectively. An intercomparison with previous SWE estimates is also performed.

All processing is conducted in the Copernicus Data Space Ecosystem (CDSE) and cloud platforms such as openEO, enabling scalable handling of large datasets and ensuring transparency, reproducibility, and open access to codes, observations, and outputs. The resulting products provide daily, high-resolution maps of SWE and ice melt, directly supporting hydrological modelling, drought and flood risk assessment, and water resource planning.

This study demonstrates how the innovative approach developed in SNOWCOP, which combines Earth observation and cutting-edge European data infrastructure, improves the estimation of meltwater from ice and snow.

Authors: *Tonelli Cristian, Premier Valentina, Braitenberg Carla and Marin Carlo*

Improving Physically-Based Snow Melt Modeling at the Sub-Grid Scale: Optimizing Terrain-Related Roughness and albedo decay time Using Satellite-Derived Snow Cover Fraction as a Model Constraint

Water stored in mountain snowpacks, like those in the Alps, is a vital resource. However, monitoring it in remote areas is challenging. While in-situ measurements are often difficult to acquire and unrepresentative, physically-based snow models provide high-resolution (HR) information but commonly neglect sub-pixel processes influencing snow accumulation, redistribution and melt dynamics.

An alternative approach is using remote sensing. By combining multi-source satellite data, HR Sentinel-2 and Landsat with daily Low-Resolution MODIS data, it is possible to derive daily, HR Binary Snow Cover (BSC) time series (Premier et al., 2021).

This study aims to improve snowmelt estimation by using satellite-derived Snow-Cover-Fraction (SCF) to constrain snowpack modeling. We evaluated how a numerical model i.e., FSM2 (Essery et al., 2024), typically calibrated at a single-point, can be adapted to better represent an entire area and improve the modeled Snow Water Equivalent (SWE).

The study was carried out on a 100-meter resolution pixel in the Dischma Catchment (CH), where HR spatially distributed hydro-meteorological-snow data are available (Magnusson et al., 2024). The core of our method is to use SCF as a model input. SCF implicitly reflects the effect of topography on snow redistribution and was integrated into the parameterization of albedo and surface roughness. Although FSM2 can already incorporate SCF, the calibration of these parameters has often been ignored due to a lack of spatialized data, with models relying on settings calibrated at single point.

We obtained our SCF dataset from BSC information at 20m aggregated to 100m. Focusing on the melting phase, the model FSM2 was initialized with snow depth measurements acquired at the SWE peak by a drone (Bührle et al., 2023). This allows to evaluate the melting model performance without considering the potential errors introduced by precipitation spatialization and snow redistribution.

Unlike ensemble approaches that vary temperature or radiation, our method controls the time decay of albedo during the melting phase using surface temperature, SCF, and surface roughness. Additionally, the roughness of the snow-free portion of each grid-cell was optimized to ensure that simulations end precisely when observed SCF reaches zero.

Our results show consistency between elevation and the flatness-index, supporting the effectiveness of this approach. Overall, this method provides a more realistic representation of numerical snow model simulations by accounting for the entire grid cell and its sub-grid variability, rather than treating the cell as a single point.

Authors: *Alex Cebulski, John Pomeroy, and Bill Floyd*

Advances in Needleleaf Forest Snow Modelling: New Insights from Western and Northern Canada

Partitioning of intercepted snowfall by forest canopies—which cover approximately 23% of the global land surface—represents an important process for predicting water resources and land-atmosphere energy exchanges. In cold, dry continental climates, researchers estimate that over half of annual snowfall may be lost to sublimation of intercepted snow from the canopy. In contrast, in warm, maritime climates the majority of intercepted snow melts or unloads from the canopy, limiting atmospheric losses from sublimation and contributes to changes in the phase and timing of precipitation reaching the ground. Despite the strong hydrological influence of snow interception, sparse observations have limited the applicability of existing theories and parameterisations of snow interception and canopy snow ablation across different forest and climate types. New measurements of subcanopy throughfall and canopy structure from aerial LiDAR, combined with high-frequency lysimeter data of canopy snow load and unloading, have advanced understanding of these processes. This has resulted in updated parameterisations that better represent enhanced interception efficiency during horizontal wind-driven snowfall and subsequent canopy snow ablation through sublimation and unloading induced by melt and wind. These new parameterisations have proven more applicable across a broad range of canopy densities and meteorological conditions. To evaluate these improvements, both new and traditional routines were implemented in the Cold Regions Hydrological Modelling platform and tested against observations of subcanopy snow water equivalent and canopy snow load across four Canadian sites: two continental climate sites (Marmot Creek and Fortress Mountain, Alberta), one subarctic site (Wolf Creek, Yukon Territory), and one coastal site (Russell Creek, British Columbia). The new parameterisations demonstrate substantially improved simulation of subcanopy snow accumulation, with mean bias reduced from -26.23 to -0.63 kg m?² and RMSE reduced from 110.61 to 44.70 kg m?² across the four sites. Simulations of canopy snow load also showed improved agreement with observations. The improved model provides a process-based framework for diagnosing how climate and vegetation influence the processes governing snowfall partitioning by needleleaf canopies.

Authors: *Tao Che, Liyun Dai, Gong Yucheng*

Snow Depth Retrieval from Passive Microwave Remote Sensing Based on CLMA-Net

Mountain snow cover plays a crucial role in the hydrological cycle, serving as a natural reservoir that regulates water supply for downstream ecosystems and meets human water demands. However, due to complex mountain terrains and strong spatial heterogeneity in snow depth distribution, current remote sensing methods and models still exhibit significant uncertainties in snow depth retrieval. To improve the accuracy of snow depth estimation in complex terrains, this study takes northern Xinjiang as the research area and develops a deep learning framework called CLMA-Net based on passive microwave remote sensing data, integrating Convolutional Neural Networks (CNN), Long Short-Term Memory (LSTM) networks, and Multi-Head Attention mechanisms. This method comprehensively considers the impacts of terrain, latitude and longitude, forest coverage, snow cover days, snow cover percentage, and temporal factors on snow depth distribution, using these parameters as auxiliary inputs along with multi-frequency brightness temperature data from AMSR-E and AMSR2 as model input features, and snow depth data from ground observation stations as target variables. Due to differences in AMSRE and AMSR2 sensor parameters, we conducted separate training and validation for each dataset. Specifically, we selected AMSR-E data from 2003, 2004, 2007, 2008, and 2009, along with corresponding ground observation station snow depth data, and AMSR2 data from 2013, 2014, 2015, 2016, and 2019 with consistent ground observations as the training set; using AMSR-E data from 2005 and 2006, AMSR2 data from 2017 and 2018, and corresponding ground observation station snow depth data as the testing set. Model performance was evaluated using indicators such as Root Mean Square Error (RMSE), Coefficient of Determination (R²), Correlation (r), and Bias (BIAS), and compared with four snow depth products: AMSRE, WESTDC, ERA5, and ML_NHSD to assess their performance in snow depth estimation. Experimental results demonstrate that our method shows significant advantages over traditional physical models and conventional machine learning methods in complex mountainous terrains: in AMSR-E data testing, RMSE was reduced to 3.14 cm, R² increased to 0.86, and BIAS was -0.03; in AMSR2 data testing, RMSE was 3.16 cm, R² was 0.85, and BIAS was 0.01. This approach effectively alleviates the common snow saturation issue in passive microwave remote sensing and more accurately captures the seasonal variation trends of snow depth, providing more accurate support for long-term snow depth prediction.

Authors: *Amy Clark, Nick Rutter, Leanne Wake and Jeff Deems*

Exploring Snow Depth Variability in Burnt Forests

Snow accumulation and melt in forests are strongly influenced by canopy structure, which governs interception, sublimation, and subcanopy shortwave radiation. When wildfire changes the canopy structure, these processes are disrupted and alter how energy and mass are exchanged between forests and snow. Such canopy loss is increasingly reshaping mountain forests; however, the impact on spatial snowmelt patterns remains poorly quantified. To address this gap, we compare pre- and post-fire canopy structure and snow conditions, using Airborne Snow Observatory (ASO) LiDAR data, to assess how wildfire-induced canopy changes modify snowmelt dynamics across eight sites in the San Joaquin River Basin (California, USA), including four that were burned during the 2020 Creek Fire.

Wildfire disturbance caused extensive canopy loss across the four burned sites, with mean canopy height reduced by 9 to 19 m and canopy cover declining by up to 90%. Distance from canopy edge (DCE), together with canopy cover and canopy height, captured how these disturbances reshaped forest structures, particularly the abundance and spatial configuration of canopy edges. Severely burned sites showed a near-total canopy removal and reduction of structural heterogeneity, whereas moderately burned sites retained some trees and edge features the preserving canopy heterogeneity. Analyses of canopy cover, mean canopy height, and DCE show that snow depth change is strongly linked to proximity to canopy edges, with steeper melt gradients across edges in unburned forests. In burned areas, these DCE-related gradients are diminished, indicating more spatially uniform and generally enhanced ablation following canopy loss. Consequently, wildfire homogenises snowmelt patterns by diminishing edge-driven contrasts in snow depth differences, resulting in faster and more spatially uniform snow loss across the landscape.

Authors: *María Courard, Chris Marsh, Josep Bonsoms, Isabelle Gouttevin, Hugo Merzisen, Juan Ignacio López Moreno, Jesús Revuelto*

Snowpack Dynamics Across Scales: the Canadian Hydrological Model in the Pyrenees

Mountain snowpacks, a critical water resource, exhibit strong spatial and temporal variability driven by diverse physical processes acting across multiple scales. These processes control the magnitude and timing of snow accumulation and ablation. Therefore, accurately representing them is essential for hydrological modeling and water resource assessment. Given the scarcity of snow observations, combining field data with physically based snow models provides a useful approach to simulate snowpack dynamics and their spatio-temporal variability. The Canadian Hydrological Model (CHM) is a novel snow modeling framework that explicitly represents lateral snow transport processes over an irregular mesh. In this work, we evaluate the implementation of CHM in three domains of the Pyrenees at different spatial scales: the Izas Experimental Cathment (~10 km²), a portion of the Tena Valley (~100 km²), and a larger section of the mountain range (~1000 km²), simulated at varying spatial resolutions. Different meteorological forcings are used to test these simulations, including SAFRAN, AROME, and ERA5, with downscaling approaches applied. Model evaluation is based on multiple data sources: point-scale snow survey stations, UAV-derived snow depth distribution maps at the catchment scale, Pléiades-derived snow depth maps at the valley scale, and a combination of these sources at the mountain range scale. We analyze snow depth magnitude and its spatial and temporal distribution using bias statistics, a spatial efficiency metric, the coefficient of variation and scale breaks derived from semi variograms. Additionally, we assess energy balance components and blowing snow and avalanches events across the studied scales. This study enhances our understanding of the influence of physical processes such as wind snow transport on snowpack dynamics and provides insights into the horizontal resolution required for accurate snow simulations across a range of spatial scales in the Pyrenees.

Authors: *Marianne Cowherd, Stefan Rahimi, Lucas Vargas Zeppetello, Manuela Girotto*

Drivers of snow drought are topography-dependent

In regions reliant on snowfall for water resources, warming temperatures diminish the storage contributions of snowpack, leading to an increased threat of snow droughts. However, warming temperatures can also contribute to increased precipitation due to enhanced atmospheric moisture. The pattern of different responses of snowfall to warming is theoretically related to topography – both elevation and the location within regions with important orographic precipitation processes. In this work, we analyze eight dynamically downscaled Earth system models at 9 and 45 km resolution from 1980 to 2100 to quantify projected snow drought frequency, type, and severity under the SSP3-7.0 scenario, i.e., an aggressive but plausible scenario with moderate greenhouse gas emissions, high aerosols, and limited climate mitigation. We find that snow drought frequency increases on average in most parts of the region, with an increasing proportion of snow droughts co-occurring with warm temperature anomalies. However, higher elevation (above 3000 m a.s.l.) regions of the California Sierra Nevada show decreases in snow drought despite increases in temperature. We then use a simple statistical model to quantify the sensitivity of simulated snowfall amounts to vapor transport (known to increase as temperatures warm) and temperature and find that vapor transport is a stronger driver of snowfall trends and interannual variability along eastern (leeward) slopes of the major mountain ranges in the Western United States, while temperature dominates the interannual variability on the western (windward) slopes. Lastly, we show that as the 21st century progresses, snowfall becomes less influenced by how much moisture is transported into a region, and the sensitivity to temperature increases.

Authors: *Pavla Dagsson-Waldhauserova, Outi Meinander, IceDust members*

Impacts of High Latitude Dust and snow-dust storms on cryosphere

High Latitude Dust (HLD) contributes to Arctic amplification and it was recognized as an important climate driver in Polar Regions in the IPCC report (SROCC, 2019). About 5% of the global dust budget comes from high latitudes, where the active HLD sources cover > 1,500,000 km2 excluding Antarctica. They are located in both the Northern Hemisphere (Iceland, Alaska, Canada, Greenland, Svalbard, North Eurasia) and Southern Hemisphere (Antarctica, Patagonia, New Zealand). Iceland is the largest Arctic as well as European desert with high dust event frequency (~135 dust days annually). About 50 % of the annual dust events in the southern part of Iceland take place at sub-zero temperatures or in winter, when dust may be mixed with snow. Phenomenon such as Snow-Dust storms has been observed and measured in Iceland and Svalbard, providing evidence on "clumping mechanism" observed in natural conditions. Several studies have shown that Icelandic dust can travel >3,500 km towards the High Arctic (>80°N) and Europe, and potentially impact the cryosphere there.

Volcanic dust from Iceland has similar impacts on snow/ice as Black Carbon in terms of albedo reduction and water retention capacity of snow. Small volcanic dust particles deposited on snow tend to form larger particles ("clumping mechanism") resulting in stronger light absorbance. However, 'effective insulation thickness' was identified as a 13 mm layer to protect the snow/ice from melt. Insulation of Kvíárjökull Glacier's part covered by debris during extremely hot summer 2021 in Iceland prevented the glacier from melting while the non-covered parts melted 20 m in height and 200 m in length during 3 months. Extreme daily glacial floods in Augusts of 2021 and 2025 in Iceland transported as much as 25 cm sediment layer of fine dust per one flood to the outwash plain Flæddur in Dyngjusandur to be suspended to the atmosphere right after the flood.

Dust-albedo-effect feedback and enhanced Arctic Amplification are linked to the HLD. There is also growing evidence that HLD will increase in the future considering the increase in erosion and more glacial melting-induced dust as a result of climate change.

Authors: *Nadeau Daniel F., Alexis Bédard-Therrien, François Anctil, Sara-Ann Piscopo, Daniel F. Nadeau*

Rain-on-snow events under the influence of atmospheric rivers: insights from observational data in the cold and humid climate of eastern Canada

Atmospheric rivers are becoming more frequent and intense worldwide. When they fall as rain over a snowpack in winter, the resulting hydrological consequences can be disastrous and difficult to forecast due to the complexity of the processes involved. This observational study examines the role of atmospheric rivers in rain-on-snow events in the cold, humid climate of southern Quebec, in eastern Canada. The study focuses also on the relative contribution of snowmelt and rain to the production of water available for runoff. Using meteorological data and snow water equivalent measured through gamma radiation attenuation from 48 stations representing 213 site-years, 124 rain-on-snow events were identified and classified according to the presence or absence of atmospheric rivers of various intensity. Early-season events were typically associated with the passage of extreme atmospheric rivers, which brought intense precipitation falling on a thin, cold snow cover. These events were responsible for the largest production of water available for runoff (an average of 63 mm), which was mainly composed of rain. In many cases, the precipitation phase changed from solid to liquid during the event, accompanied by rapid warming and high rainfall intensity. This partially melted the fresh snow layer, enhancing runoff production. End-of-season events typically occurred on thick, warm snow cover in the absence of atmospheric rivers or with low-intensity atmospheric rivers. These events produced slightly lower potential runoff (52 mm), with a greater contribution from melting. Our results also show that snowmelt is strongly correlated with turbulent heat fluxes, particularly during extreme atmospheric river events. These results provide a framework for improving flood risk assessment and suggest that further work is needed to understand how changes in the behaviour of atmospheric rivers can affect the hydrology of cold regions.

Authors: *Shaakir Shabir Dar, Olga Silantyeva, John Hult, Valtteri Hyöky, Pertti Ala-aho, Hannu Marttila, Jeffrey Welker, Lena M Tallaksen*

Snow Microstructure Regulates Isotopic Fractionation During Snow Sublimation

Sublimation is a key process regulating snow mass loss and isotopic evolution in cold regions, yet the combined influence of snow microstructure and vertical temperature gradients on snow pack isotope fractionation remains poorly constrained. We conducted controlled wind-tunnel experiments comparing sublimation-driven isotopic changes in three snow types, laboratory-produced snow, fresh natural snow, and depth hoar, under varying airflow, temperature, and humidity. A moderate, field-relevant vertical temperature gradient (-1 °C base, colder overlying air) was imposed to mimic natural snowpack conditions with upward vapor transport. Across all experiments, sublimation enriched residual snow in heavy isotopes ($\delta^{18}O$, $\delta^{2}H$) and depleted deuterium-excess (d-excess), consistent with kinetic fractionation. The magnitude and efficiency of enrichment varied systematically by snow type: fresh snow exhibited the strongest fractionation, depth hoar showed intermediate responses, and laboratory-produced snow exhibited little isotopic change despite comparable mass loss. Wind speed strongly governed both sublimation fluxes and isotope fractionation, with high ventilation producing large mass losses but weak isotopic enrichment, while low ventilation produced modest losses, but strong kinetic signals. Porosity emerged as the first-order control on isotopic change, with more open snowpack microstructures yielding greater fractionation. These results provide new evidence that post-depositional isotope modification is jointly controlled by boundary-layer dynamics and microstructure. Incorporating snow structural properties and temperature gradients into isotope-enabled snow models is essential for accurate interpretation of snowpack evolution and ice-core records.

Authors: *Jeff Deems, Kat Bormann, Tom Painter, Mark Robertson*

Peak SWE and other stories – our deepening view of mountain snowpack dynamics

In-situ snow measurements, for example from the Snow Course and Snow Telemetry (SNOTEL) networks run by the Natural Resources Conservation Service (NRCS), continue to be the backbone of seasonal snowpack monitoring supporting seasonal runoff forecasts in the western US. These networks were originally designed and deployed to support the NRCS statistically-based seasonal runoff forecast model – to supply statistical predictor variables. For example, *Peak SWE* – the maximum depth of SWE reached in a given year at a SNOTEL station or set of stations – has long been the benchmark against which seasonal snowpack states in the western US have been gauged. Peak SWE depths (in inches of water) are expressed as a percent-of-normal relative to the reference climatology (30-year median) and used as a primary predictor of likely seasonal runoff.

Due to the importance of the seasonal snowpack and the paucity of means to reliably measure basin-wideSnow Water Equivalent (SWE), applications of these data have been stretched far beyond their original intent as regression predictors. Spatial and temporal extrapolation of in-situ point measurements relies on many poorly-understood assumptions about the character and stability of landscape scale relationships between point locations and other unmeasured areas of the watershed.

A complete and accurate spatio-temporal quantification of mountain SWE – the primary seasonal storage in the mountain basin water balance – has long been a primary and high-value objective of snow hydrology. Since 2013, ASO (the NASA JPL Airborne Snow Observatory, and beginning in 2020 Airborne Snow Observatories, Inc.) has been producing basin-wide, highly-accurate maps of SWE by integrating fused lidar and spectrometer measurements of snow depth and snow albedo with the iSnobal snow physics modeloperated by M3 Works. The resulting 4-dimensional SWE data set provides new insights into the dynamics of snow accumulation and melt processes in mountain watersheds, and in particular allows assessment of long-held assumptions about snow distributions viewed only through the lens of point data.

In this presentation we explore new perspectives on our mountain snowpack reservoir in the context of operational prediction and in support of basic and applied research objectives.

Authors: *Aída del Amo Martínez, Maria Leunda, Guillermo Pérez-Villar, Reyes Giménez, Antonio Delgado-Huertas, José Ignacio López-Moreno, Ana Moreno, Miguel Bartolomé*

Isotopic composition of snow ($\delta^1?O$, δ^2H) in the Central Pyrenees (Spain): characterization and climatic controls

Understanding the climatic factors that control the isotopic composition of snow ($\delta^1?O$ and δ^2H) in the Central Pyrenees today can provide valuable insights for interpreting isotopic variations recorded in glacier ice and ice caves in terms of temperature, snow amount, storm origin (Atlantic vs. Mediterranean) and their trajectories. Post-depositional processes may also affect snow isotopic composition, including the effect of wind, sublimation, recrystallization and the mixing of meltwater with rain prior to infiltration into karst systems. A total of 429 isotopic analyses from snow events recorded between 2014 and 2018 at two sites in the Pyrenees (Formigal and Ordesa and Monte Perdido National Park) are presented. Snow sampling was carried out whenever possible the day after, or a few days after the snowfall event; in some cases, sampling occurred during the event itself. Samples were collected at different elevations along transects spanning up to 1000 m.) . Snow profiles were obtained at selected sites by taking multiple samples throughout the event record. At the event scale, some snowfalls exhibit a strong correlation between $\delta^1?O$ values and elevation ($r = 0.82$, $n = 7$, $?0.90‰$ per 100 m), with more negative $\delta^1?O$ values at higher elevations (altitude and temperature effects). Additionally, $\delta^1?O$ values tend to become more negative as the snowfall progresses (amount effect, $r = 0.96$, $n = 3$, $?0.04‰$ per cm). However, many events display inverse patterns, with heavier $\delta^1?O$ values occurring at higher elevations or with increasing snow accumulation. These trends appear to be related to sublimation, wind redistribution, or snow refreezing processes. In general, the uppermost snow deposited during storms with strong winds tends to disrupt the trend towards more negative values. At the annual scale, the dataset shows heavier values during the first snowfalls of the season, more negative values in January and February, and heavier values again during spring events. Notably, extremely negative $\delta^1?O$ values were recorded during the winters of 2015/2016 and 2017/2018 ($?26.2‰$ and $?27.5‰$, respectively), with the secondwinter being the 27th coldest since 1965 and the seventh coldest of the 21st century. Backward trajectory calculations and synoptic patterns during snowfall events, combined with field observations and isotope values, will help to identify the dominant factors controlling the final isotopic composition of snow in this sector of the Pyrenees.

Authors: *Bastien Delacroix, Fatima Karbou, Mathieu Fructus, Matthieu Lafaysse, Bertrand Cluzet*

From Sentinel 1 to CROCUS: A new data assimilation approach to snowline detection and monitoring

Snow plays a central role in the hydrological cycle, ecosystems, and the management of natural hazards such as avalanches and floods. It also represents a natural freshwater reservoir, essential for drinking water supply, agriculture, and hydropower, on which nearly one-fifth of the global population depends.

The spatio-temporal variability of snow can be monitored using different data sources, from local to regional or global scales. While in-situ measurements provide accurate snowpack information at small scales, they lack representativeness at larger scales. Satellite optical observations, at resolutions of tens to hundreds of meters, facilitate monitoring of snow cover fraction and albedo, but their usefulness is strongly limited by cloud cover. Sentinel-1 SAR measurements, unaffected by weather conditions, offer an attractive alternative. However, both optical and radar data only provide indirect information on snow properties, which requires interpretation. In addition, their long revisit intervals hinder daily snow monitoring.

In this context, numerical snowpack models such as Crocus are highly valuable, as they provide continuous simulations of snowpack physical properties. Yet, despite their level of detail, such models are affected by uncertainties related to physical parameterizations and meteorological forcing.

Data assimilation, which combines observations with simulations, therefore appears as a relevant way to exploit the strengths of both approaches. This work focuses on innovative developments enabling the assimilation of Sentinel-1 wet snow data in Crocus. Wet snow products derived from Sentinel-1 are used to extract the elevation of the snowline (altitude of continuous snow cover) and the meltline (transition between wet and dry snow) over the Grandes Rousses massif in the Northern French Alps. These same lines can also be derived from Crocus using the liquid water content (LWC), which is an intrinsic model variable. These lines can therefore serve as an observation operator to link the model with the observations. In this way, the satellite-derived elevations are assimilated into the snowpack model within the SODA-CrocO assimilation chain, which is based on a particle filter algorithm.

The preliminary results indicate substantial improvements in Crocus simulations through the assimilation of snowline elevation, which, after assimilation, aligns more closely with elevation obtained from independent sources like Sentinel-2 optical data. Improvements are also observed for other variables, such as snow depth, which shows better consistency with in-situ measurements. We will also discuss the challenges related to the combined assimilation of snowlines and melt lines, as well as perspectives for the joint assimilation of optical and radar data.

Authors: *César Deschamps-Berger, Ignacio Lopez-Moreno, Laura Sourp, Sylvia Terzago, Jesus Revuelto, Francisco Roja, Marion Reveillet*

Snowpack in spanish national parks in 2050

The future status of the snowpack is critical for assessing the impact of climate change on mountain ecosystems and human activities. Here, we focus on estimating the snow conditions in five iberian national parks in 2050. These protected areas, which have a high environmental values, host seasonal snowpack under various climatic conditions, ranging from mediterranean climate in the Sierra Nevada to alpine climate in the Pyrenees. We modeled the snowpack on 250 m grids with SnowModel forced by EURO-CORDEX meteorological data which were bias-corrected with a national reanalysis of the temperature and precipitation. We found a general decrease of the snowpack across all scenarios with an increasing impact on snow water equivalent as elevation increases but the greatest impact was on the snow melt-out date at mid-elevation. Our results emphasize the sensitivity of the projections to changes in precipitation, especially for the center and the south of the iberian peninsula. The projected increase in the frequency of low-snow winter will decrease the predictability of the summer runoff. Results also highlight the importance of mountain hypsometry for estimating changes in snow water storage at the regional scale.

Authors: *César Deschamps-Berger, Simon Filhol, Giulia Mazzotti, Florence Mazier*

Snowpack and forest in a mid-latitude mountain massif: the Pyrenees since 1950

Snow-forest interactions drive the spatiotemporal variability of snow accumulation and ablation, which in turn affect the tree growth conditions. As both the snow conditions and the forest cover are evolving in the context of global changes, their study requires considering their dynamic evolution at climatic timescales (i.e. longer than 30 years). In this presentation, we focus on the past evolution of the forest in the Pyrenees and its impact on the seasonal snowpack phenology. Our goal is to reconstruct the forest cover using archival aerial and satellite archive images, as well as contemporary forest cover maps. This time series of forest cover is then integrated into simulations of the snowpack in forest to disentangle the impact of climate change and of the forest cover change on snow conditions.

Authors: *Paolo Dezuanni, Leonardo Stucchi, Sonia Morgese, Lucia Ferrarin, Davide Fugazza, Daniele Barbone, Daniele Bocchiola*

Hydrological contribution of a debris-covered glacier: the case of Belvedere

The global cryosphere is experiencing rapid evolution as a result of increased temperature. The retreat rate is increasing
heterogeneously in the European Alps, as glacierized areas are fundamental for climatic balance and for hydrological cycles. In this context, evaluating the freshwater network of a mountain environment plays a key role for the freshwater management and policy making. The Belvedere Glacier is a debris-covered body located in the upper corner of Italy, fed by the Monte Rosa group. It has experienced a rapid retreat and elevation decrease. In this study the analysis of the Belvedere Glacier involves the application of a semi-distributed model, Poli Hydro, and a mixed Degree Day approach. The climatic data acquired from weather stations are used as input to estimate the hydrological contribution of the basin of Belvedere Glacier. Calibration analysis is performed on six parameters, through satellite images and a database of a photogrammetry monitoring campaign. Measuring surveys on site were conducted on summer 2024 and summer 2025, as a automatic weather station was installed, along with several thermistors at different depth of the debris. Results show how much ice melt and snow melt contribute to the discharge at the closing section of the river fed by the glacier.

Authors: *Biagio Di Mauro, Olga Gatti, Claudia Ravasio, Gabriele Bramati, Roberto Garzonio, Roberto Colombo*

High resolution mapping of algae and dust on snow in an Alpine proglacial environment

Snow optical properties can be significantly altered by the presence of impurities such as mineral dust, black carbon, and biogenic particles. Among these, snow algae blooms and mineral dust, typically visible as reddish patches during the melting season, are a widespread phenomenon both in alpine and polar regions. They have recently attracted increasing attention for their role in decreasing surface albedo and accelerating snowmelt, thereby contributing to the positive feedback mechanisms.

In this study, we investigates the optical properties of snow affected by algal blooms and mineral dust in the Brenta Dolmites (Southern Rhaetian Alps, Italy), through a field campaign conducted on 5th – 6th July, 2021. Snow samples (N = 32) with different algal and dust concentrations were collected for optical microscopy counts and dust load determination. In situ hyperspectral reflectance data were acquired with a Spectral Evolution SR-3500 spectroradiometer, while high-resolution RGB imagery was collected via a DJI Mavic 2 Pro drone. Snow surface properties such as SSA, LWC and density were measured using the SLF Snow Sensor. We evaluated the effectiveness of the I_680 index, a scaled band integral at 680 nm that is known from the literature to be sensitive to the presence of algae (Painter et al. 2001; Di Mauro et al. 2024). Our results show a strong correlation ($R^2 = 0.6$) between I_680 and algal concentration (for cells <15 µm in diameter), confirming its suitability for snow algae detection. Furthermore, we developed a classification map of algal blooms and mineral dust from RGB orthophotos by exploiting the distinct convex shape of the snow spectral signature in the three RGB channels when algae are present, contrasting with the flat or concave response typical of clean snow or snow darkened by dust. Future work will extend the I_680 index to current (e.g., PRISMA, EnMAP) and future (e.g. CHIME, SBG) satellite hyperspectral imagery to map snow algae and dust concentration from space over wider snow fields.

Authors: *Federico Di Paolo, Matteo Dall'Amico, Ballarin Filippo, Robin Castellani, Federico Di Paolo, Anna Paola Lonardi, Stefano Tasin, Chiara Zambon*

30 years (1991-2021) Snow Water Equivalent reanalysis dataset over the Padan Plain, Italy

In the framework of the AgriClima project, addressed to the risk mitigation in agriculture due to climate change, we have produced a Snow Water Equivalent (SWE) dataset over the Padan Plain (Italy) over 30 winter seasons (1991-2021).The Padan Plain is one of the most productive agricultural area in Europe, where water availability and cold spells strongly affect crop yields. In fact the snow has a significant effect: first of all, it prevents the ground from freezing, furthermore, although to a lesser extent than in the mountains, it slows down the flow of precipitation downstream and facilitates slower percolation into the ground.

For this reason, understanding the long-term dynamics of SWE represents a key step to support sustainable agricultural practices and climate adaptation strategies in the region.

The simulations have been carried out using the physically-based GEOtop model, taking as input ERA5-Land reanalysis of meteo input (i.e., air temperature, water equivalent of precipitation - either solid or liquid, relative humidity, wind velocity, incoming short wave radiation, air pressure, snow depth, and cloud transmissivity). One of the common problems in simulating snow evolution in the plain is the absence of in situ snow gauges. In order to validate and correct the model we used, as a reference dataset, an almanac containing a collection of snowfall events observed in the Po plain, representing a reasonable reconstruction of the total accumulation over the whole winter period. Finally, MODIS-retrieved Snow Cover Area (SCA) maps have been used to validate the results on the most relevant snow events recorded during the period.

The dataset, produced at 500 m resolution at daily granularity over 30 years, represents the first attempt to reconstruct snow cover over large plains in Italy. On a scientific point of view it is very valuable as it allows to quantify the effects of climate change over a very vulnerable environment, where a few degrees Celsius are causing a disruptive change over the snow presence. Such dataset can be further integrated with the SWE dataset produced by Dall'Amico et al. (2025) in the mountainous area of Po River basin, to have a comprehensive dataset of SWE for long-term hydrological analyses and drought mitigation purposes.

Authors: *Federico Di Paolo, Matteo Dall'Amico, Stefano Tasin, Maxim Lamare, Moritz Plattner, Johannes Schöber*

Earth Observation-driven Snow Water Equivalent simulations for a near real-time snow monitoring system

In the Alps, most precipitation during winter falls as snow at altitudes above 1.000 m, where it accumulates and remains stored in the snowpack until the melting season, when it returns in the hydrological cycle and is partly used to sustain downstream water. Thus, snow is a critical component of the mountain cryosphere, playing a significant role in shaping the hydrology and climate dynamics.

In recent decades, thanks to the large and open availability of Earth Observation (EO) data, the monitoring of snow at a global scale has been enabled, with different snow variables observed from satellite, such as Snow Cover Area (SCA), Snow Water Equivalent (SWE) and snow depth or height of the snow (HS).

Recently, advanced models for snow evolution have been improved by assimilating information coming from EO, in order to enhance the performance and more accurately represent the reality.

A common problem in running physically-based models to simulate the snowpack evolution is the coherence between the simulated and observed SCA. The problem lies in the simulation of two physical processes: a) accumulation, where one needs to estimate the limit of the snowfall line (i.e., the lowest elevation of solid precipitation), and b) melting, where one needs to follow the increase in elevation of the snow presence over the terrain during snow ablation.

Here we present a new method for the assimilation of EO-retrieved SCA maps into the physically-based GEOtop model, driven by the ERA5-Land meteo input. EO SCA maps are used to correct two different physical parameters:

- Air temperature, to adjust the snowfall line during the accumulation season; this can help in reducing the temperature bias present in the input dataset;
- Melting rate, to adjust the snowline during the melting season; this can be used to correct any bias in the melting rate evaluated by the physical model.
  Our methodology has been tested over the Austrian Alps, during the 2022/2023 winter season, in the framework of the GTIF Austria project, in order to evaluate the performance of the modeling chain before activating a near real-time service for the 2025/2026 winter season over the Austrian Alps. Results show a significant enhancement in the performances, thanks to the assimilation of EO-retrieved SCA maps. Such methodology can be easily reproduced over other mountain chains, thanks to the availability of mid- to high-resolution EO data worldwide.

Authors: *Oscar Dick, Benoît Laurent, Neige Calonne, Pascal Hagenmuller*

Dry snow metamorphism at high spatial and temporal resolution: impact of temperature, temperature gradient, and initial snow

Snow physical properties result from the complex 3D arrangement of ice and air at the grain scale, referred to as snow microstructure. Describing snow microstructure and predicting its temporal evolution are keys for snowpack models, such as CROCUS or SNOWPACK. Currently, the representation of the microstructure in these models is incomplete or not fully satisfying, as shown by some discrepancies when compared to field or lab observations. For example, SSA of new snow simulated in CROCUS tends to decrease faster than observations. Furthermore, certain characteristics of snow microstructure which significantly affect snow properties are not taken into account, such as structural anisotropy. Efforts towards a more physically-based description of the microstructure have been made. They, however, pointed out the lack of experimental time series of snow metamorphism with systematic variations of the evolution conditions. Such experimental dataset would be necessary to develop or evaluate evolution laws of microstructural properties valid for a large range of snow evolution, as encountered in nature.

In this work, we use X-ray tomography measurements to characterize the temporal evolution of microstructural properties of snow under dry snow metamorphism at high spatial and temporal resolution. To do so, we designed a snow-metamorphism cell to continuously control the temperatures at the boundaries of a centimeter-sized snow sample while snow is being scanned. A large range of conditions of snow evolution was explored: mean snow temperature from -3 to-17°C, snow temperature gradient from 0 to 100 K/m, and three initial snow samples with varying snow type, density, and specific surface area. A total of 21 snow metamorphism experiments was carried out. Each experiment lasted for 7 days, and scanning was performed every 4 hours. We obtain a unique set of time series of 3D tomographic images of snow under dry metamorphism for varying evolution conditions. As a first step, we present here the impact of temperature, temperature gradient, and initial snow on the snow evolution through a selection of microstructure properties, such as specific surface area or snow curvature distribution, computed on the 3D images. The long-term objective is to improve the description of the microstructure in the current models by testing the evolution laws against our experimental time-series and suggest improvements of the laws, if needed.

Authors: *Pablo Domínguez-Aguilar, Jesús Revuelto, Javier Bandrés, Eñaut Izagirre, Francisco Rojas-Heredia, Pablo Ezquerro, Jorge Pey, Juan Ignacio López-Moreno.*

Mixing UAV and in situ measurements to understand the spatio temporal variability of snow impurities in a Pyrenean site

The presence of impurities on the snowpack surface can alter its optical properties and thus modify its energy and mass balance, causing earlier melting. In the Pyrenees, the occurrence of African dust deposition events is one of the major sources of snow Light-Absorbing Particles (LAPs). However, this deposition is not spatially uniform, making it hard to correctly estimate the intensity of an event just from distributed manual sampling. In this study, an Unmanned Aerial Vehicle equipped with a multispectral camera has been used to monitor LAPs distribution through the winter season of 2025 in a 40 ha experimental catchment in the Western Pyrenees. Additionally, in-situ sampling took place to measure LAPs concentration, snow spectral albedo in the 400-900nm range and snow Specific Surface Area. This information was used to select and calibrate the spectral indices maps in order to generate high-resolution (0.20m) maps of surface LAPs concentration in the catchment. The sequence of maps provided good insights on the spatial patterns of LAPs accumulation and showed their evolution as the season advanced and different layers (events) of African dust mixed on the surface due to snowmelt. Additionally, the sediment input from higher sections of the catchment increased toward the later days of the season. The higher LAPs concentrations were found in the topographically depressed areas, where meltwater channels form on the snowpack and sedimentation from upstream sources occur.

Authors: *Luis Durán, Álvaro González-Cervera and Belen Rodríguez-Fonseca*

Trends, Low-Frequency Variability and Teleconnection Patterns of Wintertime Weather and Snowfall in Sierra de Guadarrama

Mountains play a crucial role in the climate system across multiple temporal and spatial scales. They also serve as essential sources of resources, such as freshwater, and host a rich diversity of ecosystems. Their influence on human development and natural environments is particularly pronounced in semi-arid regions like the Sierra de Guadarrama. This mountain range, part of the Central System in the Iberian Peninsula, has been the subject of official meteorological observations since the mid-20th century. However, knowledge of rainfall and temperature variability, as well as the factors driving these patterns, remains limited for this important region of Spain. Since 1940 meteorological observations have been conducted in a regular basis, moreover, a methodology has been developed to extend observations from 1900 to the present by integrating ERA-20C reanalysis data with in-situ measurements. This approach has enabled the creation of longer time series and a more comprehensive analysis of large-scale teleconnection patterns and climate variability than was previously possible. The analysis encompasses trends in temperature, snow precipitation, and snowpack duration. Identified variations in precipitation and temperature provide valuable insights for estimating potential changes in seasonal runoff and rainfall intensity. Such information is highly relevant for organizations responsible for managing the region, as it supports the development of adaptation strategies under emerging climate scenarios and enhances seasonal to decadal climate predictions.

Authors: *Pere Esteban Vea, Marc Prohom Duran, Jordi Cateura Sabri, Juan Ignacio López-Moreno, Jordi Cunillera Grañó*

Elevation-dependent warming in the Pyrenees: Observed trends, new elevational transects and drivers' detection

Correspondence to: Esteba Vea, Pere pere.esteban@gencat.cat) Servei Meteoeològic de Catalunya, Dr Roux 80 08017 Barcelona, Catalonia, ES.

As part of the LIFE-SIP project Pyrenees4Clima (2024–2032), this presentation outlines ongoing research focused on detecting Elevation-Dependent Warming (EDW) in the Pyrenees and identifying it main drivers.

On one hand, trend analysis based on high-elevation climate records from Andorra, Spain, and France has yielded promising results, providing preliminary evidence of a potential EDW signal.

On the other hand, since summer–autumn 2025, new transects equipped with meteorological sensors (temperature and humidity) have been operational in the central Pyrenees, in the Bonabé (Catalonia) and Panticosa (Aragón) areas. These transects follow, as closely as possible, the recommendations of the Unified High Elevation Observing Platform (UHOP), and span from mid-elevations (1500–1600 m) to mountain crests (2700–3050 m).

In the near future, the research will also explore the relationship between EDW and atmospheric circulation patterns, as well as the influence of snow cover—or its absence—on warming trends.

Authors: *Pablo Ezquerro, Nacho López, Jesús Revuelto, Oriol Monserrat, Claudia Pérez, Marc Oliva, Josep Ventura, Pedro Espín*

Evaluating the performance of X-band and C-band SAR data over mountain areas and snow coverage. Tena Valley case of study.

Differential and Multitemporal interferometry (DInSAR and MT-InSAR) has been extensively proved to be a valuable tool to detect ground deformations but also worked to provide insightful results over glacial and periglacial environments to map rock glaciers and snow avalanches. Since many authors have experienced the usefulness of SAR data in this context, there is a scarcity of works taking advantage of high spatial (3x3 m) and temporal (1-7 days) resolution from X-band dense constellations like COSMO-SkyMed.

Rock glaciers are tongue-shaped landforms representing the most visible geomorphological evidence of permafrost on high mountain slopes. During the last decades, many rock glaciers from the European region have suffered an acceleration, with some examples of increased hazard after sudden displacements and collapses linked those changes to the evolution of climate-related conditions.

Tena valley, located in central Pyrenees range, is affected by different geological hazards like landslides and floods. Several landslides and paleo-landslides have been inventoried in the upper part of the valley, many of them with recent activity detected and characterized using SAR data from different satellites. Regarding snow-related processes, the existing rock glacier located in the western face of Algas peak (also known as Argualas rock glacier) has been studied measuring from 5 to 16 cm/year of horizontal surface displacement. Also, snow avalanches regularly affect the ski resorts and roads of the valley.

In this initial work DInSAR results based on X-band data over a Pyrenean range are presented and compared with those from C-band Sentinel-1 (both EGMS and ad-hoc processing). Interferograms under summer and winter conditions have been also calculated to understand the challenges and limitations of the technique and the different radar bands in mountainous areas. Coherence and amplitude are explored to detect snow surface changes, while phase is expected to provide rock glaciers surface displacement and a change of Snow Water Equivalence (SWE) proxy. SNAP ESA software and PSIG CTTC processing chain have been used to process the data.

Authors: *Mateja Fabe?i?, Michal Jení?ek, Johnmark N. Acheampong*

The Fast and the Slow: Snowmelt Dynamics and Runoff Partitioning in Czech Mountain Catchments

Mountain catchments are increasingly vulnerable to the impacts of climate change. Rising air temperatures are driving a transition from snowfall to rainfall, reducing snow storage, shortening the duration of the snow season, and causing earlier and more frequent snowmelt events. Consequently, this raised the question of whether changes in catchment processes could alter catchment transit times and, in turn, accelerate the water cycle. This study aims to quantify 1) whether the increasing number of partial snowmelt periods during winter resulting from increasing rainfall compared to snowfall affects the partitioning of the snowmelt runoff into soil and groundwater components, 2) how it affects selected hydrological signatures in late spring and early summer, and 3) examines the influence of catchment characteristics on the above processes.

To investigate changes in the runoff components, we used long-term simulations from 68 mountain catchments in Czechia covering the period from 1965 to 2019, using a conceptual, bucket-type catchment model. We analysed temporal trends in the fraction of fast (event) and slow (baseflow) runoff responses, calculated as monthly or seasonal fractions of the individual components to total runoff. We then aimed to identify the dominant seasonal runoff component by analysing its distributions and the shifts over the past decades. The Spearman rank correlation coefficient was calculated to quantify the monotonic relationship between fast and slow runoff components and maximum snow water equivalent (SWE) across individual seasons and months. Additionally, we investigated how the catchment characteristics influenced these relationships to provide a more comprehensive understanding of water cycle dynamics across different mountains in Czechia.

The preliminary results indicate that both fast and slow components' absolute values are decreasing, with the fast component dropping faster in spring. Fast runoff dominates in spring, with the shift toward slow runoff occurring in May. Years with the high maximum SWE contribute to the increase of the fast runoff component in March and April, probably due to a shift in snowmelt. Ultimately, the influence of SWE on the selected hydrological signatures becomes more pronounced with region than elevation.

Authors: *Alicia Fallows, Rosemary Willatt, Tom Mitchell, Daniel Feltham*

Investigations into flooding of snow on sea ice and snow ice formation: cold laboratory experiments with snow and sea ice, and remote sensing of slush.

In the polar regions, Arctic sea ice covers on average 15.5 million square kilometers and Antarctic sea ice covers around 18.5 million square kilometers. This sea ice is often covered by snow, and often with complex snowpacks. *Snow ice* formation occurs when sea ice floes undergo flooding, resulting in a slush mixture of snow and saltwater atop the sea ice, that subsequently refreezes. Flooding is a prevalent process in the Antarctic due to its relatively thicker snowpack and thinner sea ice, meaning that negative freeboards can occur and seawater is able to permeate into the snowpack. The process is also becoming more likely in the Arctic due to increased precipitation. It is important to understand more about flooding, slush, and snow ice formation, such as the conditions for formation, properties and evolution, in order to understand the possible contribution to the sea ice mass balance, how it impacts our understanding of sea ice thickness in the polar regions (particularly from satellite remote sensing), and generally how these processes may alter the physical properties of the snow and ice system.

I have investigated snow and sea ice in a cold laboratory environment, initially performing investigations on snow created in the laboratory to see how it compares to natural snow, and performing preliminary investigations on brine transfer into snow, towards simulating flooding in the lab. In parallel, analysis has been carried out on some in-situ radar data to understand the impact of a flooded snow pit site on the radar signal, showing interesting returns in the snowpack. The aim is to progress this to analyse satellite data of known flooded areas from in-situ observations, to try and analyse any signals of flooding from within the snowpack at a larger scale.

Authors: *Steven Fassnacht, Enrique Morán Tejeda, Brian M. Steen, Antonio-Juan Collados Lara, Daniel McGrath, Stephanie Kampf, Helen Flynn, Noah Caldwell, Camille Stevens-Rumann, Joachim Meyer*

Rain and Snow after Peak Needs to be Considered to Model Melt

Historically snowmelt has been modelled starting with the amount of snow that exist at or about peak. However, the addition of water to the snowpack during snowmelt can be substantial. The temperature index approach is simple and when considered temporally dynamic to account for increased solar loading and decreased albedo, is still used in many operational settings. We evaluate the impact of considering precipitation during snowmelt in estimate the melt factor (MF) used in the temperature index approach We examine daily data from Snow Telemetry (SNOTEL) stations located in the Colorado USA, including snow water equivalent (SWE), air temperature (Ta), precipitation and snow depth over the last 20 years. While many of the SNOTEL stations have been operating since the 1980s, air temperature monitoring was added in the 1990s and snow depth monitoring was added in the 2000s. The air temperature sensor was altered current with the snow depth sensor installation, which created a discontinuity in the Ta time series. A further error has been identified in the Ta time series that will be considered here. The phase of the precipitation added during snowmelt was also evaluated and identified as snow by an increase in snow depth and rain otherwise.

Authors: *Steven Fassnacht, Christina C. Chow, Jeffrey D. Niemann, Jeffrey E. Derry, Elayna R. Bump*

Sweet Snow Measurements using a Cosmic Radiation Neutron Rover

Accurate knowledge of snow water equivalent (SWE) is important in any snow dominated region of the world for water resources, climate, ecology, tourism, etc. But SWE is difficult to estimate since it often varies greatly over a variety of spatial and temporal scales. Cosmic Ray Neutron (CRN) rovers can potentially provide SWE data, especially to complements other measurement approaches. A CRN rover counts the number of neutrons in a particular energy range, and that neutron count is inversely related to the amount of hydrogen near the sensor. A CRN rover can collect neutron counts within a minute, and each measurement indicates a weighted average of the hydrogen within an approximate 200-meter radius of the sensor. Thus, a rover can be mounted on a vehicle and used to map SWE patterns. While stationary CRN sensors have been used for SWE measurements in open areas, few studies have used a CRN rover to measure SWE. This study tests the capabilities and limitations of a CRN rover for mapping SWE along plowed/paved roads, which has operational implications. The study focuses on 70-km highway in the San Juan Mountains of Colorado between Ironton Park and Purgatory ski area, with an elevation range of 800 meters. The rover was driven at 40 km/h along the road and parked at 10 field sites. At each field site, snow cores and snow depth measurements were used to estimate the SWE within the rover footprint. After accounting for the road effects, the rover's estimate of SWE are quite promising compared to the field estimates, and nearby Snow Telemetry stations.

Authors: *Helen Flynn, Daniel McGrath, Joachim Meyer, Noah G. Caldwell, Camille Stevens-Rumann, Stephanie K. Kampf, Steven R. Fassnacht, Andrew R. Hedrick, Kelly Elder*

Evaluating iSnobal model performance in wildfire-impacted basins in Colorado, USA: the role of landcover parametrizations

Seasonal snow, a critical water resource in the Western United States (U.S.), varies considerably across elevations, aspects, and landcover types. Recent large fires in the Southern Rocky Mountains and across the Western U.S. have altered forest structure leading to earlier and faster snowmelt in burned areas. This study is aimed at evaluating and improving the capability of a physics-based snow energy and mass balance model, iSnobal, to predict snowpack evolution across post-fire landscapes with a focus on landcover parameterizations, specifically vegetation height and canopy extinction and emissivity. Using climate forcing data from the High-Resolution Rapid Refresh (HRRR) numerical weather prediction m (odel, iSnobal was run over five consecutive post-fire water years (2021-2025) in the Cameron Peak, Colorado, USA burn scar (2020; 84,443 ha) with two configurations: one with the 2016 (pre-fire) LANDFIRE dataset and one with time-varying (post-fire) LANDFIRE datasets. Model outputs were evaluated against a network of five automated weather stations in the study domain located across a range of topographic conditions. Model runs with post-fire landcover datasets showed better agreement with the station data in predicting snow disappearance date (SDD) (4 ± 5 days earlier with landcover updates vs 30 ± 13 days after without landcover updates). Despite this improved agreement, the model runs with post-fire landcover datasets still overestimated net shortwave radiation and underestimated net longwave radiation in the burned areas (average of 48 ± 9 W/m^2 and 57 ± 4 W/m^2, respectively, from April 1 through SDD). The 2025 Colorado wildfire season was the worst fire season since 2020 with over 80,900 ha burned, demonstrating the importance of having accurate water forecasting capabilities post-fire. Future components of this work will include modeling different burn severities, testing the sensitivity of the model to vegetation height, applying the most accurate version of the landcover parameterizations to a basin within the East Troublesome Fire burn scar (2020; 78,433 ha), and using forest-ecology-informed recovery scenarios to predict snowpack dynamics 5, 10 and 20 years into the future. This research provides a critical evaluation of iSnobal model performance in post-fire areas, and highlights recommendations on model set-up to improve performance in these regions.

Authors: *Adrià Fontrodona-Bach, Harsh Beria, Denis Groshev, Thomas E. Shaw, Catriona Fyffe and Francesca Pelliciotti*

Global snow surface sublimation hotspots based on ERA5-Land

Sublimation of snow represents a potentially important but poorly constrained component of the hydrological cycle, especially at large spatial scales. Many studies have estimated snow sublimation at local scales, reporting a wide range of estimated rates, ranging from 5-90% of winter snowfall. Although it is well established that dry, windy and sunny conditions favor snow sublimation, a modern, global-scale assessment of the climatic regions where sublimation occurs and is important is lacking. Existing global efforts to estimate sublimation are limited by coarse resolution (~250 km) reanalyses data, leaving a critical gap in our understanding of sublimation's contribution to the water balance across climates and regions. Here we present a global analysis of potential snow surface sublimation hotspots using ERA5-Land reanalysis at 0.1° (~10 km) resolution. We examine the climatic and topographic drivers of snow surface sublimation, quantify their contribution relative to total snow ablation, and map their distribution across the globe. Comparisons with sublimation observations from eddy-covariance flux towers demonstrate that ERA5-Land underestimates sublimation rates, but performs favorably compared to estimates from other reanalysis (GLDAS, GLEAM, MERRA-2) products. Our results highlight regions where surface sublimation may be a significant component of the hydrological cycle, with implications for water resources, glacier mass balance and snow–atmosphere feedbacks. Important uncertainties remain, particularly in complex mountain regions where the resolution of ERA5-Land data cannot fully capture sublimation processes. Furthermore, drifting and blowing snow sublimation are not resolved in ERA5-Land. Future efforts should refine these global estimates by using higher-resolution simulations and improved representations of snow–atmosphere interactions to identify sublimation hotspots over complex terrain.

Authors: *Kévin Fourteau, Kaoane Jondeau, Clément Cancès, Marie Dumont*

Thermodynamics of snow: a fundamental truth or a simple tool?

Thermodynamics is ubiquitous in snowpacks and provides a consistent basis to study several physical processes at play, from heat transfer to mass transport and phase changes. In the last couple of years, we worked on deriving a thermodynamically-consistent description of snow and snowpacks, encompassing a breath of physical processes. Our original motivation was applying the so-called "entropy-methods" of applied mathematics in order to derive well-behaved numerical models. Here, we present some conclusions from this endeavor and future questions we want to address. Notably, using thermodynamics first principles highlights some underlying relations between various the physical properties and processes at play in snow, for instance the thermal capacity of snow and the saturated vapor pressure. But respecting all these relations and conditions to obtain strict thermodynamically-consistent models appears cumbersome to do in practice. This calls for compromises between physical rigor and pragmatism, in order to fully exploit the advantages of thermodynamics without overcomplexifying snowpack models.

Authors: *Davide Fugazza, Leonardo Stucchi, Luca Pedrotti, Daniele Bocchiola, Guglielmina Adele Diolaiuti*

Monitoring snow and ice fed mountain streams: the IdroStelvio network

We present the main outcomes of the IdroStelvio project, a continuous (2010-present) monitoring initiative developed through cooperation between the Stelvio National Park Authority, the University of Milano, and Politecnico di Milano. The project established and maintained a hydrometric network monitoring 11 high-altitude streams predominantly fed by snow and ice meltwater. The monitoring system, covering approximately 32% of the park's area, and more than 90% of glacierized catchments therein, provides a comprehensive view of the hydrological dynamics of this sensitive Alpine region. IdroStelvio represents one of the most extensive and long-standing case studies of hydrological monitoring in glacierized environments, both in Italy and internationally. Beyond reporting the structure, evolution, and scientific outputs of the network, we distills the operational experience gained into a set of practical guidelines for the monitoring of snow-ice fed mountain streams. These guidelines address site selection, sensor configuration, maintenance protocols, and data validation strategies, aiming to support the replicability of similar systems in other high-altitude regions. The collected data are valuable for hydrological modeling, scenario analysis, and water resource planning under climate change of ice and snow-melt fed mountain catchments. The IdroStelvio experience may serve as a reference framework for future monitoring initiatives in sensitive alpine environments.

Authors: *Adam Christopher Funnell, Peter James Thomas*

MESSENGER-SWE – in-situ SWE measurement using optical fibre sensing mats

Accurate in-situ measurement of Snow Water Equivalent (SWE) is essential to calibrate models based on remote measurements from radar and imaging. SWE measurement using weight is a gold standard for determining the total water content of a snowpack. However, single point measurements from snow scales or snow pillows are insufficient to calibrate large areas with varying terrain and weather. Each individual point measurement can show inaccuracies due to thermal discontinuity from the surrounding ground and may not be representative of the whole catchment area. Conventional ground-based sensors also require extensive and expensive groundwork, and installation using heavy machinery in remote locations. Manual sampling can provide high accuracy SWE reference measurements, but infrequently and only in areas accessible for inspection.

MESSENGER sensors are made from optical fibre threaded within a carefully structured rubber mat; the optical signal strength passing through the fibre is directly affected by the weight of snow pressing on the mat surface. Layers of plastic provide mechanical protection and control the distribution of snow loading over the sensitive mat. The resulting sensor is lightweight and easily transportable to field locations, with sufficient battery power for hourly readings sent via mobile networks over multiple snow seasons. Multiple mats can be combined to automate transect or grid SWE sampling, improving the accuracy of in-situ data for remote sensing models. The sensor design has been developed using feedback from SnowHydro 2024, and continuous improvements to sensor performance are reported.

Conventional wisdom for in-situ SWE sensors is that larger surface areas give more accurate resulting measurements. This is due to snow bridging which could reduce weight loading on small sensors, and sensor edge effects arising from thermal discontinuities with the ground. We present promising results for small rectangular sensors less than 1m² in area, and thin strip sensors only 20 cm wide. There is good agreement between these smaller area sensors and existing 25 m² snow scales. Furthermore, the sensors require no major groundwork for installation, and are only 25 mm in thickness to minimise thermal discontinuity with surrounding ground.

Small sized optical sensors are attractive for increasing in-situ measurement coverage, due to their ease of installation and operation. Measurements from several field trials in Norway, including currently live data from an ongoing trial, are presented. The sensors have been installed close to existing SWE measurement stations, allowing direct comparisons between MESSENGER-SWE mats and established in-situ measurement methods.

Authors: *Diego García-Maroto, Elsa Mohino, Luis Durán, Álvaro Gonzaléz-Cervera*

Iberian mountains snow cover in global km-scale climate simulations: verification and future changes in the nextGEMS IFS-FESOM model.

Mountains are a key natural resource for many parts of the world, particularly in Mediterranean regions such as the Iberian Peninsula, where disruptions caused by climate change can have enormous consequences. However, due to their coarse resolution, current climate models cannot properly represent the complexity of orographic processes. Storm-resolving models, with resolutions finer than 10 km in the horizontal, offer a path forward to provide high-quality information for local adaptation.

In this work, we assess the ability of one of such models, the IFS-FESOM developed as part of the EU-NextGEMS project, to represent the seasonal snow cover in the main Iberian mountain ranges and to evaluate the effects of climate change there. The model is evaluated against four high-resolution reanalysis products as well as satellite data and station observations. We show that, despite a somewhat positive bias in the length of the snow cover season and the total number of snowfall days, the model can represent features of the snow climatology, such as its elevation dependency, seasonal cycle, and mean covered area, successfully within the range of uncertainty of the reference products and observations. In addition, the model projection under the SSP3-7.0 scenario shows a marked reduction of the snow season across almost all of Iberia, with low- to mid-elevations and the southernmost mountain ranges displaying the greatest reductions. These changes are mainly related to a reduction in snowfall days, caused primarily by rising temperatures but also by decreasing precipitation, particularly in southern and Mediterranean sectors. Our results suggest that kilometer-scale simulations might be able to provide local climate projections of snow variables in complex terrain without the need for specific regionalization.

Authors: *Matthieu Denisselle, Florence Marti and Simon Gascoin*

Improving snow fraction estimation from Sentinel-2 data for the Copernicus Land pan-European HR-WSI production

Among its bio-geophysical products, the Copernicus Land Monitoring Service (CLMS) produces and disseminates information on snow, ice, and water bodies at the European scale.

This data is compiled into the High Resolution Water, Snow, and Ice (HR-WSI) portfolio which covers snow properties on land (snow cover, state conditions, and annual synthesis). Among those indicators, the Fractional Snow Cover (FSC) product is generated in near real-time (NRT) from Sentinel-2 for the entire EEA38+UK area. The product is pixel-wise with a spatial resolution of 20 m x 20 m. This data is managed by the European Environment Agency.

Snow-covered pixels are detected using the Let-It-Snow (LIS) processor. LIS operates on Sentinel-2 L2A products, which are surface reflectance images that include a cloud and cloud shadow mask, generated by the MAJA atmospheric correction processor (Gascoin et al., 2019). The LIS algorithm is capable of reclassifying some pixels labeled as clouds as either snow or no snow, increasing the number of non-cloudy observations.

The FSC is currently determined from the normalised difference snow index (NDSI) based on a linear relationship (Hall et al., 2002; Salomonson and Appel, 2004). It was however calibrated for MODIS data and is furthermore limited under shaded areas conditions due to high noise in the NDSI. Additionally, there is a higher uncertainty in the FSC for pixels initially identified as clouds in the L2A product but reclassified as snow-covered by LIS.

In this study, we aim to enhance FSC estimation by calibrating a new model using a dataset of very high-resolution satellite images (Pléiades and SPOT 6/7) acquired across Europe, from which accurate reference snow maps can be produced. The model will also incorporate additional variables available to LIS, such as other Sentinel-2 spectral bands and data derived from a digital elevation model. We will evaluate both linear and machine learning approaches and present the current performance of the Copernicus FSC products, along with the improvements achieved through the proposed methods.

Gascoin, S., Grizonnet, M., Bouchet, M., Salgues, G., Hagolle, O., 2019. Theia Snow collection: high-resolution operational snow cover maps from Sentinel-2 and Landsat-8 data 22.

Hall, D.K., Riggs, G.A., Salomonson, V.V., DiGirolamo, N.E., Bayr, K.J., 2002. MODIS snow-cover products. Remote Sens. Environ., The Moderate Resolution Imaging Spectroradiometer (MODIS): a new generation of Land Surface Monitoring 83, 181–194.

Salomonson, V.V., Appel, I., 2004. Estimating fractional snow cover from MODIS using the normalized difference snow index. Remote Sens. Environ. 89, 351–360.

Authors: *Simon Gascoin*

How much snow is there on Earth?

Previous estimates have discarded mountain regions where microwave remote sensing data are not usable and ignored the southern hemisphere. Thanks to the increased resolution and accuracy of climate reanalyses, the question of how much seasonal snow is formed on Earth every year can be answered at global scale with less uncertainty than ever. Based on previous evaluation studies of gridded snow products, I selected the ERA5-Land reanalysis (~9 km grid spacing) to estimate the mass of seasonal snow on Earth over 1970-2020. The results suggest that the seasonal snow mass varies between 0 and 6000 Gt in the northern hemisphere and between 0 and 250 Gt in the southern hemisphere. The maximum snow mass occurs in March in the northern hemisphere and in September in the southern hemisphere. The 10-year average of the maximum snow mass in the northern hemisphere has declined by 500 Gt from the 1970's to the 2010's. The trend in the southern hemisphere is less consistent.

Authors: *Olga Gatti, Biagio Di Mauro, Carlo Marin, Roberto Garzionio, Giacomo Bramati, Valentina Premier, Claudia Notarnicola, Simone Pettinato, Edoardo Cremonese, Paolo Pogliotti and Roberto Colombo*

Snow melting phases detection using apparent thermal inertia, radar data and numerical modelling

Understanding the dynamics of snowmelt is essential for hydrological forecasting, natural hazard assessment, and water resource management in both mountainous headwater catchments and downstream lowland systems. In recent years, multiple strategies have emerged to assess melt onset and dynamics, including in situ measurements, physically based snowpack models, and microwave and thermal satellite data. However, few studies have directly compared these approaches to evaluate their consistency in detecting snowmelt phases.

This study presents a multitemporal analysis (2016–2021) integrating three different snow detecting methods over two Alpine sites in the Aosta Valley (Western European Alps): Torgnon (2160 m a.s.l., sub-Alpine) and Cime Bianche (3100 m a.s.l., Alpine). The dataset includes: (i) ground meteorological measurements from Automatic Weather Stations (AWS), used to force the physically based SNOWPACK model and obtain key snowpack variables such as snow temperature, liquid water content (LWC), and snow water equivalent (SWE); (ii) optical and thermal infrared measurements used to retrieve the Apparent Thermal Inertia of snow (APs), which is sensitive to variations in surface temperature and albedo; and (iii) C-band Synthetic Aperture Radar (SAR) backscatter time series from Sentinel-1 (orbits 66, 88, and 139), sensitive to changes in liquid water content and snow structure.

We focused on identifying the three characteristic phases of snowmelt—warming, ripening, and output—defined by specific thresholds. The onset, end, and duration of each phase were extracted independently from the three datasets and compared.

Findings show that, although based on different physical principles, radar, thermal, and model-based approaches provide consistent information on snowmelt timing when systematically compared. In particular, the comparison between Sentinel-1 SAR backscatter and APs highlights their ability to detect the onset and progression of melt phases in a coherent way. Results show that melt progression is site-dependent: at the sub-Alpine site, melt phases begin earlier and are shorter, whereas the Alpine site exhibits delayed and prolonged transitions due to colder conditions and wind-driven snow redistribution.

Future satellite missions such as ESA's LSTM and NASA's SBG-TIR will significantly enhance thermal monitoring of the snow surface, while current hyperspectral missions like PRISMA and EnMAP enable the retrieval of key snow properties (e.g. light-absorbing impurities and liquid water content). These developments open new perspectives for remotely sensing snowmelt phases across both mid-latitude and polar regions.

Authors: *Emmy Stigter, Katrina Gelwick, Emmy Stigter, Michael McCarthy, Maximiliano Rodríguez Moreno, Alvaro Ayala, Franziska Zilker, Sergio Contreras, Nacho López-Moreno, Simone Fatichi, Dirk Karger, Achilles Jouberton, Francesca Pellicciotti and Walter Immerzeel*

Drought, snowmelt, and vegetation stress in the Pyrenees: insights from ecohydrological modeling

Droughts are globally becoming more frequent and severe in a warming climate, with significant implications for mountain ecosystems and downstream water resources. In Spain's Ebro River Basin, the second largest on the Iberian Peninsula, these challenges are particularly acute. Covering 85,362 km², the basin supplies water to over 3.2 million people and supports extensive agriculture. However, declining precipitation (>10% since the mid-20th century) and rising temperatures have led to reduced snowpack and earlier snowmelt onset in the Pyrenees, contributing to more frequent water shortages, lower crop yields, and increased wildfire risk throughout the Ebro region?. This study assesses how vegetation in high-elevation Ebro tributaries in the Pyrenees responds to meteorological droughts and the extent to which snowmelt dynamics buffer ecological and hydrological drought impacts. Using the Tethys-Chloris land surface model, a process-based ecohydrological model, we simulate ecohydrological responses to droughts for the period 2000–2010, which includes several extended dry spells. The model is run at high spatial resolution (250 m) and is forced with downscaled, bias-corrected ERA5 climate reanalysis data to account for the high spatial variability in meteorological conditions in mountain regions. To evaluate the Tethys-Chloris simulations, we compare model outputs with both in-situ observations of snow and satellite-based products, including MODIS-derived snow cover extent, leaf area index (LAI), and Normalized Difference Vegetation Index (NDVI). These comparisons assess the model's ability to capture observed snow dynamics, vegetation stress and ecosystem variability during droughts. Understanding the feedback mechanisms between snow, ecology and hydrology will improve our ability to predict how mountain ecosystems respond to drought and their role in regulating downstream water availability. These insights are critical for assessing future drought risks to water resources and ecosystem services in the Ebro River Basin.

Authors: *Reyes Giménez, Ana Moreno, Marc Luetscher and Miguel Bartolomé*

Snow-Driven Recharge of Alpine Karst Aquifers: Isotopic Evidence from the Collarada Massif (Central Pyrenees)

Karst aquifers in mountainous regions represent major reservoirs of freshwater. In alpine areas, large altitudinal and topographic gradients confer specific recharge characteristics, strongly influenced by snow accumulation and melt dynamics. This study investigates the isotopic composition of precipitation and karst spring discharge in the Collarada Massif (Southern Central Pyrenees) to better understand recharge processes in high-altitude karst systems. Precipitation (rain and snow) was sampled across different elevations to quantify the spatial variability driven by the altitude-topographic effect in the area. Concurrently, meteorological data on air temperature and precipitation amount were collected. The isotopic composition of precipitation showed a clear seasonal signal, with enriched values during summer and depleted values during winter. The seasonal variation is largely controlled by temperature. Snow analyses revealed that isotopic signatures are not only altitude-dependent but also strongly affected by post-depositional processes, leading to significant spatial heterogeneities in snow isotopic values. The isotopic composition of groundwater closely resembles that of winter precipitation (ca. $-10‰$ for $?^{18}O$), indicating that snowmelt represents the dominant source of karst aquifer recharge. These findings allow for a better delineation of the hydrological catchment and highlight the nival regime, which governs both storage and temporal distribution of water resources throughout the year. This study points to the significant dependence of alpine karst systems on snow dynamics. In light of the projected changes in snowfall amounts and distribution under climate change scenarios, karst aquifers must be regarded as highly vulnerable reservoirs, thus foreseeing a significant challenge to the long-term sustainability of mountain water resources.

Authors: *Manuela Girotto, Rashmi Shah, Thomas Van Der Weide, Hans-Peter Marshall, Andrew Schwartz*

Testing a Tower-Based P-band Signal of Opportunity Approach for SWE Retrieval

Accurately quantifying snow water equivalent (SWE) over mountainous regions remains a major challenge for the snow remote sensing community. Recent work has highlighted the potential for active microwave-based methods, such as from C- or L-band Interferometric Synthetic Aperture Radar (InSAR) approaches. By measuring phase shifts between two coherent radar acquisitions, the C- and L-band InSAR can retrieve changes in SWE accumulation. Here, we explore a novel P-band signal of opportunity approach, which leverages existing geostationary satellite transmissions (used for communication) and tower-based dual-antenna receivers to estimate SWE from an interferometric approach. We deploy the tower-based receivers on a site in the Central Sierra Snow Lab (Soda Springs, California). The site experiences a wide range of snowpack conditions typical of a maritime climate, including deep snow, midwinter melt events, and rapid transitions. It includes a complementary set of in-situ measurements available for validation purposes. The presentation will describe the experimental setup and preliminary results.

Authors: *David Gochis, Jeff Deems, Thomas Painter, Logan Karsten, Kevin Sampson, Kat Bormann*

Operational process-enabled hydrologic modeling for water management decision-support: A Case Study in California's Sierra Nevada

Highly accurate, complete basin mapping of snow water equivalent (SWE) from airborne lidar has emerged as an operationally-viable observation that can be used in data assimilation and forecasting. These data
provide much needed information on the highly variable spatial patterns and amounts of SWE which, in turn,
drive runoff and water resources availability. In order to maximize the utility of these new data, hydrologic
forecasting models should be able to effectively utilize the high-resolution spatial descriptions of SWE as well as other key physical, snowpack variables such as multi-spectral snow albedo observations. The modern generation of fully-spatially distributed, process-based hydrologic models are well suited to capitalize on these novel data in order to provide continuous, cross-scale, i.e. from small headwaters to large river basins, skillful analyses and predictions of water resources. Results from a multi-year forecasting effort that operationally ingests airborne snow measurements from the Airborne Snow Observatories, Inc. (ASO) measurement platform into the WRF-Hydro modeling system over the Sierra Nevada of California, USA will be provided. The results document the relative impact of assimilating ASO-observed snowpack on seasonal water supply forecasts from the study region. Additional context will discuss how these new observations are used as a component of the overall management of the State's highly stressed water resources. The study's findings suggest that implementation of a complete end-to-end observational, assimilation and forecasting capability can add significant benefit in terms of limiting large forecast errors and providing additional confidence in water supply forecasting and decision support.

Authors: *Christian Göhrig, Pia Ruttner, Yves Bühler*

Interannual Consistency of Snow Depth Distribution: Extended Multi-Year Analysis from Dischma Valley, Switzerland

While interannual consistency of relative snow depth distribution and snow-terrain relationships are well-established, comprehensive validation remains limited. Studies typically achieve either large spatial extent, high resolution, or long temporal coverage, but rarely all three. Although the assumption of consistency in relative snow depth distribution is routinely applied in snow modeling, hazard assessment, and climate change studies,the limits of this assumption remain poorly defined. This validation gap introduces substantial uncertainty into applications where prediction reliability is critical.

We present an extended timeseries analysis using a 13-year dataset of snow depth maps at the estimated peak of winter (2010-2025, missing 2011 and 2018). From 2010 to 2016, we used the Leica ADS 80/100 systems and from 2017 and ongoing we are using the Vexcel UltraCam system, both mounted on a fixed-wing aircraft. The photogrammetric dataset covers approximately 112km² of the Dischma Valley, Switzerland at 2m spatial resolution with an average vertical accuracy of snow depth between 0.15-0.35m. Spatial correlation analysis reveals broad consistencies with varying correlation coefficients ranging between year pairs. Detailed local analysis demonstrates the existence of multiple recurring patterns in relative snow depth distribution, independent from absolute snow depth. While terrain control is of well known influence in snow depth distribution, the assessment of patterns of multiple scales and years provides insights in the sensitivity of snow-terrain relationships. Our findings highlight the importance of additional variables like climate, snowpack characteristics and avalanche activity.

This unique 13-year, high-resolution airborne dataset enables systematic sensitivity analysis of interannual consistency of relative snow depth distribution. We will assess how varying conditions modulate snow-terrain relationships and identify the spatial and temporal scales at which consistency assumptions hold or break down. These findings will establish reliability thresholds for snow distribution predictions and show when additional process complexity must be considered in model applications.

Authors: *Nicolás González-Santacruz, Francisco Fernandoy, Jorge Pey, Kumiko Goto-Azuma, Motohiro Hirabayashi, Jon Arrizabalaga-Iriarte, Raúl R. Cordero, Sarah Feron and Sérgio Henrique Faria*

Isotopic Records and Black carbon Effects in the Godwin-Austen Snowpack: A Radiative and Geochemical Perspective from the Central Karakoram

The high-mountain cryosphere, composed primarily of glaciers and both seasonal and perennial snowpacks, acts as a natural reservoir that releases meltwater during spring and summer, sustaining downstream ecosystems, agriculture, and human populations. Within the global cryosphere, high-mountain regions are especially sensitive to atmospheric warming and changing precipitation regimes, which are reducing snow cover duration, accelerating glacier retreat, and destabilizing meltwater availability. Superimposed on these climate-driven changes, the deposition of light-absorbing impurities (LAIs), such as black carbon (BC), can significantly lower snow albedo, triggering earlier melt onset and enhancing ablation rates. These radiative effects are further amplified by feedback mechanisms involving snow grain metamorphism, impurity enrichment, and surface exposure.

We present two integrated case studies from the Central Karakoram based on snow samples collected on the Godwin-Austen Glacier and at high-altitude camps along the K2 climbing route. First, stable water isotopes ($\delta^{18}O$, δD) are used to infer seasonal accumulation layers and establish a relative chronology of the snowpack. These profiles enable us to assess the timing of black carbon deposition measured by single-particle soot photometry (SP2) and to evaluate its impact on albedo. Backward air-mass trajectories computed using the HYSPLIT model further support the identification of potential BC source regions. The second study analyzes the ionic (e.g., Ca^{2+}, Mg^{2+}, SO_4^{2-}) and trace-element (e.g., Sr, Ba, Li) composition of the snowpack via ion chromatography and ICP–MS, providing insights into the contribution of crustal versus anthropogenic sources.

Authors: *Álvaro González-Cervera, Luís Durán*

High-resolution snow trends simulations in Sierra de Guadarrama

The snowpack in the mountains is a vital source of water for both high-altitude regions and adjacent lowlands, and has a significant impact on local economies due to its influence on tourism, communications, logistics, and recreational risks. However, mid-altitude snow cover is declining due to climate change (IPCC-2021), which has become a critical issue for water management. Despite its importance, the lack of comprehensive knowledge is due to the scarcity of well-distributed observations of mountain snow cover and specific simulation tools. This knowledge gap is most pronounced in Mediterranean mountain regions, where intricate growth and ablation processes, high spatial variability, and high interannual variability pose challenges for models. To address these challenges, high-resolution models (<1 km) have been developed, but they often involve significant computational costs. One alternative is to use nested intermediate complexity models with simplified physical processes that allow for high-resolution climate simulations. Within the framework of the FIRN project, the ERA5 atmospheric reanalysis (ECMWF), the Intermediate Complexity Atmospheric Research model (ICAR, NCAR), and the Flexible Snow Model (FSM2, University of Edinburgh) have been nested to obtain high-resolution simulations in Sierra de Guadarrama (Central system, Spain). These high-resolution simulations allowed us to map snow cover trends and identify spatial heterogeneities driven by topographical and meteorological factors.

Authors: *Henna-Reetta Hannula, Roberta Pirazzini, Julia Martin, Aleksi Rimali, Eric A. Sproles, Antti Mikkonen, Hannakaisa Lindqvist and Aku Riihelä*

UAV-Based Insights Into HDRF and Albedo Dynamics in Boreal Snow Environment

Surface albedo estimates derived from satellite-based optical sensors play a crucial role in understanding surface–atmosphere energy exchanges, especially in cold environments where snow and ice prevail. Improving and validating these satellite products is difficult due to the limited availability of ground-based measurements of spectral albedo and quantities related to the bidirectional reflectance distribution function (BRDF). In-situ observations are often confined to footprints of only a few tens of centimetres—or are collected at a single fixed point, which limits their spatial representativeness. This study addresses that gap by exploiting recent advances in unmanned aerial vehicle (UAV) instrumentation to characterize the spatial heterogeneity of surface spectral albedo and the hemispherical-directional reflectance factor (HDRF) in the 390–950 nm range.

A dedicated five-day campaign was conducted in April 2023 at the Finnish Meteorological Institute's Arctic Research Centre in Sodankylä, Finland, coinciding with Sentinel-2 and Landsat-8 satellite overpasses. Measurements were collected above two contrasting surface types: snow-covered open bogs and sparse pine forests. UAV-based systems acquired vertical profiles of spectral and broadband albedo up to 100 m altitude and multi-angle HDRF observations at approximately 25° angular resolution, with footprint diameters ranging from 7 m to 14 m over snow-covered bogs and from 18 m to 23 m over sparse pine forests. Continuous ground-based spectral albedo and irradiance data were recorded to complement airborne observations, while RGB orthomosaics, snow-specific surface area (SSA), snow temperature, and density measurements were used to support interpretation.

Preliminary analysis indicates that vertical variations in spectral albedo are primarily driven by heterogeneity within the UAV measurement footprints. Multi-angle HDRF measurements over snow-covered bogs demonstrated consistent directional patterns across footprint sizes. The HDRF variability within the same measurement pattern was higher at near-infrared wavelengths compared to the visible spectrum. Reflectance generally decreased from the visible to the near-infrared at nadir, while forward-scattering differences were more modest. In contrast, HDRF retrievals over sparse forests were more complex due to mixed contributions from snow, canopy, and shadows. Sentinel-2 surface reflectance–derived albedo values agreed with UAV-based estimates but were slightly higher overall.

Though labor-intensive, UAV surveys provide flexible, spatially representative data. Future work will broaden sampling across solar geometries and snow types, compare with goniometer data, and evaluate results against a BRDF model over the NIR range. This enables improved integration of UAV-based reflectance data with BRDF modelling and satellite retrievals to enhance understanding of albedo-driven radiative processes in boreal snow environments.

Authors: *Víctor Herráiz-López, Adrián Subías Martín, Iñigo Salinas, Carlo Marin and Rafael Alonso*

Approaching Broadly Applicable Model for Snow Permittivity Through Full-Wave FEM Simulations

Electromagnetic methods for retrieving snowpack properties, such as height, density, and liquid water content (LWC), usually rely on prior knowledge of the permittivity of the snowpack. However, the absence of a broadly applicable permittivity model of the snow under different physical conditions limits the accuracy of the measurements. Radar methods, in-situ electromagnetic devices to measure LWC of the snowpack, and the snow water equivalent measurement from the time delay of global navigation satellite system (GNSS), among others, would benefit from a wide-ranging permittivity model of the snow. The generation of new datasets performing permittivity and other physical properties measurements of the snow is a difficult and time-consuming task. However, electromagnetic simulation approaches could facilitate the development of a broadly applicable permittivity model.

In this work, we present three-dimensional full-wave finite element method (FEM) electromagnetic simulations of the permittivity of dry snow at 5 GHz using a realistic microstructure model and the well-established permittivity models of pure ice. The presented simulated method differs from those in previous literature, as we simulate the plane wave transmittance and reflectance of a snow slab. It is experimentally realizable and allows the determination of both the real and imaginary parts of the permittivity. The method is readily adaptable to study the effects of microstructure variations and to include non-zero LWC in realistic microstructures at different frequencies.

From our initial findings, we have observed that for dry snow with a fixed microstructure of rounded grains but varying ice content, the real part of the permittivity calculated via FEM simulations aligns well with established experimental models, such as the Mäztler model. While the real permittivity does not change significantly with temperature shifts, the imaginary part is far more sensitive. Our FEM simulations accurately capture these variations, whereas current models based on experimental measurements seem to struggle to properly describe this temperature-related variation. This discrepancy likely stems from the difficulty of precisely measuring the small losses inherent in dry snow.

Hence, from the preliminary results, we believe that the proposed FEM simulation method can significantly improve our understanding of the temperature dependence of the dry snow permittivity. It also offers the possibility of extending the simulations towards wet snow, different frequencies, and varying realistic microstructures, allowing for the development of broadly applicable permittivity models.

Authors: *Jose David Hidalgo Hidalgo, David Pulido Velazquez and Antonio Juan Collados Lara*

Assessing recent snow trends in the Sierra Nevada (Spain) by using a cellular automata model

Snow-dominated mountain systems in semi-arid regions are highly sensitive to climatic variability and serve as key pilots to monitor global climate change. These snow reservoirs play a critical role in regulating water availability, sustaining ecosystems, and supporting downstream populations that depend on seasonal snowmelt. However, in the Sierra Nevada (Spain), one of the most important Mediterranean mountain ranges, a consistent and spatially distributed assessment of long-term snow cover trends is still lacking. In this study, we simulated snow cover for the period 1951–2021 using a cellular automata model driven by climate data (AEMET 5 km), and evaluated these simulations against MODIS observations for 2000–2020. Statistical significance analyses (Mann-Kendall and t-test) were applied to snow cover variables and snowline elevation, together with an assessment of the relative influence of climate drivers on snow cover anomalies. Results indicate that during the past 70 years, temperature increased by 0.84–1.54 ºC, while precipitation decreased at –2.3 to –7.5 mm per year, depending on location and elevation. Simulated snow cover time series reveal an overall reduction in snow cover extent and significant negative trends of –0.6 to –0.15 days per year in areas with consistent seasonal snowpack (? 2300 m a.s.l.), with the strongest declines observed on the western slopes. Concurrently, the overall snowline rose at a rate of 1.4–1.8 m per year, corresponding to an elevation gain of approximately 100 m at present. Temperature emerged as the dominant driver of snow cover anomalies, with a relative importance of 69.3 %. These findings highlight the vulnerability of semi-arid mountain snowpacks to ongoing warming and underscore their value as sentinels of climate change in Mediterranean environments.

Authors: *Jose David Hidalgo Hidalgo, Enrique Merino Arribas, David Pulido Velazquez, Steven Fassnacht and Antonio-Juan Collados Lara*

Combining NARX and LSTM artificial neural networks for predicting snow cover area under climate change scenarios

Snow-dominated mountain regions are highly sensitive to climate variability and change, acting as natural observatories for detecting early climate signals. Understanding and predicting snow coverdynamics in these areas are essential for assessing the impacts of climate change on water resources, ecosystems, and mountain hydrology.

Recent studies have reported significant reductions in snow cover across various systems in the context of climate change. Moreover, growing evidence suggest non-linear relationship between climate variables and snow evolution under global warming context, making traditional linear models less effective in capturing such complex interactions. In this context, artificial neural network models provide flexible and powerful frameworks for modeling the snow cover evolution under the context of climate change.

In this study, we developed and tested a hydrid deep learning model combining Nonlinear Autoregressive Networks with Exogenous inputs (NARX) and Long Short-Term Memory networks (LSTM) for predicting snow cover area. The model was applied over six snow-dominated catchments representative of different climatic conditions: three semi-arid regions (Sierra Nevada, Spain; Southern Rocky Mountains, USA; and Andes, Chile) and three humid regions (Alps, Italy; Caucasus Mountains, Georgia; and Himalaya, Nepal). Historical climate variables were obtained from ERA5-Land reanalysis data and training dataset were derived from MODIS snow cover observations. Future snow cover projections were estimated for two future period (2051–2070 and 2081–2100) under two emission scenarios – SSP 2 RCP 4.5 (E1) and SSP 5 RCP 8.5 (E2) – using statistically downscaled climate forcings derived from LARS-WG stochastic weather generator.

The NARX-LSTM model demonstrates good agreement with training dataset as reflected by high values of $R2 \sim 0.9$ and modeling efficiency metrics: NSE = 0.68–0.96 and KGE = 0.73–0.97. Projected results indicate mean reductions in snow cover ranging from 12.46 % to 39.53 % under E1 and from 16.69 % to 58.09 % under E2. These findings highlight the potential of hybrid deep learning approaches for improving snow cover modeling and informing climate adaptation strategies in mountain regions.

Authors: *J. Michelle Hu, Joachim Meyer, Alvaro Robledano, Mathis Leeman, and S. McKenzie Skiles*

Assessing a Distributed Process-based Snowmelt Model informed by Remotely Sensed Snow Albedo Across the Upper Colorado River Headwater Basins

Albedo is a principal control on net solar radiation and regulates snowpack energy absorption. Despite highly variable primary processes exerting pronounced effects on the energy balance during the melt season, most process-based models use empirical time decay functions to represent snow albedo, leading to potential inaccuracies in the timing and rate of snowmelt. To address these shortcomings, recent efforts have been made to directly assimilate remotely sensed snow albedo into a snow energy balance model (i.e., iSnobal) driven by numerical weather prediction outputs (High Resolution Rapid Refresh; HRRRv4) to refine net solar radiation inputs. Initial work in Colorado's East River Watershed demonstrated improved accuracy in simulating both melt magnitude and timing.

We evaluate this new modeling approach using MODIS snow albedo products produced from the open access Snow Properties Inversion from Remote Sensing (SPIReS) algorithm and assess outputs across a range of watersheds in the Upper Colorado River Basin, an important source of water to more than 40 million people and 29 federally recognized Tribes. We compare simulations of snow accumulation and melt dynamics from this approach (HRRR-SPIReS; 100 m) with the University of Arizona snow products (UA; 800 m) and outputs from the National Water Model (NWM; 1000 m), developed by the National Oceanic and Atmospheric Sciences. Modeled snow representations are benchmarked spatially against data from airborne lidar (ASO; 50 m) and temporally against in situ snow measurements from automated weather stations (SNOTEL). Simulated snow water equivalent (SWE) from HRRR-SPIReS are also compared with operational forecasts from the Colorado River Basin Forecasting Center.

We present a parseable comparison with publicly available modeling outputs against accessible reference datasets to contextualize model and dataset performance. In ungauged and sparsely monitored basins, process-based models driven with numerical weather prediction and refined with satellite remote sensing products have the potential to provide temporally and spatially complete information on watershed state. This work is conducted in support of these efforts.

Authors: *N. Imperatore, M. Lafaysse, S. Gascoin, M. Dumont, S. Guével, A. Mauss, J.-B. Hernandez, M. Verna*

Towards the assimilation of VIIRS snow cover into a distributed ensemble simulation system

The assimilation of remotely sensed products is a powerful technique to reduce the uncertainties of snowpack simulations in mountain regions. In particular, moderate resolution (100-1000m) fractional snow cover (FSC) satellite products are known to be beneficial in different data assimilation systems.

Météo-France is developing methods for real-time assimilation of satellite products, for its upcoming ensemble distributed snowpack simulation system, EDELWEISS. The Visible Infrared Imaging Radiometer Suite (VIIRS) snow cover products represent today the best compromise between spatial resolution (375 m), revisit time (3 platforms with daily passes), data policy and mission status (guaranteed until the end of the decade) for an operational application. However, these products have been rarely used in the snow science community and their performances are unknown in the context of data assimilation. Thus, we characterize the uncertainty of VIIRS observations in mountainous areas, in particular for the NASA official distribution (VNP10A1 and VJ110A1 products) and a Météo-France internal FSC product based on VIIRS observations. To do so, we perform a detailed comparison with Sentinel-2 Theia 20 m FSC considered as a reference given its much higher resolution.

We show that VIIRS snow cover fraction mean square error is in the range 6-14 %, although the uncertainty can be higher in some challenging observation classes (mixed pixels, forest and shades). Moreover, we leveraged the complementarity between the three VIIRS platform acquisitions to reduce cloud cover without affecting accuracy, what led us to develop a new VIIRS FSC daily multi-platform composite. Hence, we compare this product to snowpack simulation outputs in order to gain insight about snow cover fraction parametrization for the future model. This will pave the way towards the first experiments of assimilation of our product into EDELWEISS using a particle filter.

Authors: *Eñaut Izagirre, Sérgio H. Faria, Francisco Fernandoy, Dieter Tetzner, Juan Ignacio López-Moreno and Iñaki Antiguedad*

Snowpack signals and noise: stable isotope insights from the Cordillera Darwin Icefield (54–55ºS)

The Cordillera Darwin Icefield (CDI, 54–55° S) lies at the heart of the Southern Hemisphere westerlies and offers rare potential for high-latitude paleoclimate records outside Antarctica. However, it is unclear whether seasonal climate signals are preserved in the snowpack.

We present the first spatially distributed study of snow stratigraphy and stable water isotopes ($\delta^{18}O$, δD, d-excess) from five snowpits (1–2.2 m deep) dug in March-April 2022 in the Roncagli, Francés and Italia glacier accumulation zones (1350–2150 m a.s.l.). Stratigraphic analysis revealed strong contrasts between wind-swept, compacted sites and lee-side basins with fresher accumulation. Isotope values ranged from -9.3‰ to -19.1‰ ($\delta^{18}O$) and -58‰ to -146‰ (δD), with a d-excess of 5–16‰. Crucially, none of the profiles show a clear seasonal cycle. Instead, the isotopic layering reflected event-scale snowfall, which was later blurred by melt-freeze cycles, percolation horizons and wind redistribution. To determine the origin of moisture, HYSPLIT back-trajectories were run for the austral summer 2021–2022. More than 75% of the trajectories originated from the Amundsen and Bellingshausen Seas and the high-latitude Southeast Pacific, confirming a dominant marine source and the role of the CDI as a receptor for unaltered oceanic moisture.

Our results show that the stratigraphy of stable isotopes in the CDI is determined by synoptic storm events and post-depositional processes rather than seasonal temperature gradients. This emphasizes the value of the CDI for capturing the large-scale ocean-atmosphere dynamics at the sub-Antarctic margin. It will therefore be crucial for future ice core drilling in one of the most remote and least studied glacierised regions of the Southern Hemisphere to identify the locations where isotopic integrity is best preserved.

Authors: *Jonas-Frederik Jans, Firoz Borah, Zhenming Huang, Ghislain Picard, Leung Tsang, Hans Lievens*

Comparison of snow microwave radiative transfer models to represent Sentinel-1 C-band backscatter in the European Alps

Snow microwave radiative transfer models (RTM) are a powerful tool to enhance our physical understanding of snow-radar interactions. They are capable of disentangling an aggregated backscatter signal into its respective components, which are the signal reflected from the ground, the vegetation and the snow. Furthermore, RTMs have been employed to retrieve SWE using inverse modelling approaches and have provided simulations concerning expected snow-covered backscatter response to strengthen satellite mission proposals.

Previous research has demonstrated the potential of Sentinel-1 co- and cross-polarized backscatter observations to monitor key observables of snow dynamics, such as snow depth, snow water equivalent and snow melt onset. During snow accumulation the increase in the ratio of cross- to co-polarized backscatter can be leveraged to retrieve snow depth or snow water equivalent. However, this conceptual relation furthermore depends on the presence of forest cover, the occurrence of snow melt-freeze cycles and the amount of snow accumulation, and does not explain the underlying physical driving mechanisms. Therefore, to further investigate the relationship between snow and backscatter, we suggest a comparison of physics-based RTMs.

Additionally, recent findings show that the local incidence angle, i.e., the angle between the local surface normal and the incoming radar signal, shapes the behavior of co-polarized backscatter with snow depth accumulation. At low local incidence angles the co-polarized backscatter often seems to increase as snow depth increases, while at medium to high local incidence angles this is much less prevalent. To analyze if this behavior is captured by RTMs, their simulations were compared at four locations with in situ snow depth stations and both a low and high local incidence angle overpass of Sentinel-1. Furthermore, several synthetic experiments were performed to capture the underlying cause of this phenomenon.

The Snow Microwave Radiative Transfer model (SMRT) and the Dense Media Radiative Transfer model-Bicontinuous (DMRT-Bic) were selected for aforementioned comparisons. SMRT was selected because it is a repository of well-established radiative transfer model configurations comprising a variety of microstructure and electromagnetic models. In contrast, DMRT-Bic is a standalone radiative transfer model specifically built to represent the interaction of microwaves with snowpacks consisting of irregularly shaped and closely packed ice crystals. Both models were tested in one and two layered conditions with several parameter configurations to best represent the C-band co- and cross-polarized backscatter at multiple local incidence angles.

Authors: *Michal Jenicek, Ondrej Nedelcev, Michael Matejka, Kamil Laska, Zbynek Engel, Jan Kavan*

The role of snowmelt, glacier melt and rainfall in streamflow dynamics on James Ross Island, Antarctic Peninsula

The Antarctic Peninsula is currently experiencing a rapid increase in air temperature, significantly impacting the entire ecosystem, including the runoff processes. It is therefore important to understand the water balance dynamics within this sensitive environment. Although water availability is a critical factor in polar ecosystems, the mechanisms of runoff generation in many regions remain inadequately understood. Therefore, we conducted an analysis of the variability in rainfall, snowfall, and glacier contributions to runoff in relation to climate variability within a small, partially glaciated catchment on James Ross Island, located in the northeastern Antarctic Peninsula.

The hydrological model HBV was employed to simulate the runoff process from June 2010 to May 2021 at a daily temporal resolution. The model was calibrated using both seasonally measured discharge data and glacier mass balance records. Simulation results indicated a negative mass balance for Triangular Glacier in nine out of eleven study years, with an average annual mass loss of 49 mm water equivalent. Approximately 92% of the annual runoff occurred between October and May. Typically, peak runoff occurred in the latter half of the summer season, attributable to the combined effects of glacier melt and snowmelt. The predominant source of runoff (76%) was snowmelt, followed by glacier melt (14%), and rainfall (10%). Higher total annual runoff was observed during warmer and drier years, associated with increased glacier melt runoff. Conversely, the contribution of snowmelt to total runoff was more significant in colder years with higher precipitation. Our simulation further revealed the occurrence of substantial runoff events outside the usual peak summer runoff period not covered by conventional measurements and highlighted the need for continual runoff measurements to improve the model performance.

Authors: *Vincent Haagmans, Giulia Mazzotti, Clare Webster and Tobias Jonas*

How montane forests shape snow cover dynamics across the central European Alps

A substantial fraction of seasonal snow is stored in mid-latitude montane forests, serving as an essential temporal water storage. Across vast areas, snow cover dynamics are the result of processes equally controlled by forest structure, topography, climate, and weather variability. As data availability has limited our ability to disentangle how these four key controls interact across landscapes within complex topography, most forest snow studies have focused on only one or two of the controls. In this study, we employed the process-based FSM2oshd forest snow model framework for an in-depth analysis of the current state of forest snow water resources across the central European Alps. Over the 8 years analyzed, forest snow accounted for 20–30 % of the total snow storage in midwinter. In the various effects of existing forest cover on snow, pronounced differences were found depending on elevation, aspect, region, and year. While the presence of forest usually led to a decrease in peak SWE, it decelerated snowmelt, often leading to a later snow disappearance date, particularly on south-facing slopes. However, variability between years and regions was strong enough to shift or even reverse such trends, where snow-scarce years accentuated relative differences in the effects of forests on snow cover. With forest disturbances projected to increase and snow storage to further decline, enhanced complexity of snow cover dynamics in montane forests is to be expected. This places more emphasis on understanding how the effects of key controls such as forest structure, topography, and weather interact.

Authors: *Jorge Jorge-Ruiz, Juha Lemmetyinen, Ioanna Merkouriadi, Manu Holmberg, Jouni Pulliainen, Jaan Praks*

Repeat-pass differential InSAR for Snow Water Equivalent Retrieval of boreal areas

The rapid growth of the space sector has transformed satellite-based Earth Observation (EO) into a cornerstone of environmental monitoring, resource management, and scientific research. Over the past decade, the number of EO satellites has increased dramatically, enabling continuous global monitoring of physical, chemical, and biological processes at multiple spatial and temporal scales. This expansion, coupled with advancements in data processing, has driven new applications in climate science, agriculture, hydrology, and natural hazard assessment. However, the unprecedented data volume poses challenges in terms of analysis, interpretation, and integration with ground-based measurements.

Remote sensing technologies can be broadly classified as active or passive systems. Passive instruments detect naturally emitted or reflected radiation, while active sensors emit energy and record the backscattered signal. Synthetic Aperture Radar (SAR) has emerged as a powerful active and coherent system capable of providing high-resolution, all-weather observations, with particular value for cryospheric studies. Among cryospheric variables, snow plays a critical role in regulating Earth's climate through its high albedo and insulation properties, while acting as a major freshwater reservoir. Despite its importance, accurate estimation of snow water equivalent (SWE) from space remains a challenge due to the complex interaction of microwaves with snow microstructure, vegetation, and terrain.

This presentation explores the potential of repeat-pass differential Interferometric SAR (d-InSAR) for SWE retrieval over boreal forest regions. The work combines tower-based and satellite SAR observations with modeling approaches to evaluate the sensitivity of interferometric phase to snow accumulation and environmental factors. The work focuses on understanding the sensitivity of interferometric phase to changes in snow mass and the environmental factors affecting coherence. A semi-empirical model linking interferometric phase to SWE variations is implemented to evaluate the feasibility of snow mass retrieval under different frequency bands and temporal baselines. The research also examines how forest structure, air temperature, and snow properties influence microwave propagation and attenuation. Using both ground-based and satellite radar observations, the study explores the relationship between snow accumulation, vegetation attenuation, and coherence loss. Furthermore, advanced statistical modeling and multichannel interferometric approaches are developed to improve SWE retrieval accuracy by mitigating noise, resolving phase ambiguities, and exploiting spatial continuity in snow accumulation patterns.

Overall, this research advances the understanding of snow–microwave interactions and provides a methodological foundation for future satellite missions such as NASA–ISRO SAR (NISAR) and ESA ROSE-L, enabling more reliable snow mass monitoring from space.

Authors: *Joschka Geissler and Markus Weiler*

Adapting forests to enhance winter snow storage and gradual snowmelt

In snow-dominated catchments, snow acts as a natural water reservoir by storing precipitation during winter and releasing it gradually during spring and summer. Depending on climate, topography and landcover, this seasonal buffering can mitigate drought or flood risks. In this context, forests are a challenge and can be a potential at the same time: Because forests cause snow amounts to vary on very small spatial and temporal scales, snow dynamics in these environments are specifically challenging to measure and predict. Because forests will likely undergo major changes in the context of climate change, adapting its structure might open possibilities to enhance the seasonal buffering effects in these environments that cover major parts of the northern hemisphere. In that regard, it is essential to better understand how and in what extent forest structure influences snow dynamics. This study leverages existing machine learning concepts that generalize the effects of forest structure on spatiotemporal snow dynamics in the form of homogeneous clusters. A model is trained on existing datasets with the aim to predict such spatiotemporal snow clusters for entire mountain ranges and to improve our understanding of the drivers behind the formation of these clusters. With these tools and insights, we analyse what forest structures promote snow storage and heterogeneity and thereby enhance the seasonal buffering effect of the forest snowpacks. Our results show that improving the heterogeneity of forests for example with medium-sized canopy gaps (~10–20 meters diameter) can increase snow accumulation by up to 10% compared to dense or open-canopy conditions. These structures also lead to more gradual and sustained snowmelt during spring, potentially reducing peak runoff and extending water availability into drier periods. Our findings call for a more integrative perspective on current forest management practices that should, alongside with forest influences on biodiversity, carbon storage and other forest services also include their impacts on regulating snowpack dynamics and downstream water supply.

Authors: *Arttu Jutila*

SNOWBALL: Synergy of models, observations, and remote sensing for Arctic snow and ice

Warming climate is causing rapid changes in the Arctic cryosphere, with profound implications for regional and global climate systems. Snow-covered lake and sea ice regulate energy exchanges between the surface and atmosphere, yet their changing properties under amplified Arctic warming remain poorly understood. SNOWBALL, a new four-year project funded by the Research Council of Finland, addresses this challenge by embracing the synergy of three complementary approaches: numerical modelling, in situ observations, and microwave remote sensing.

At its core, the project couples two advanced models: the spatially distributed physics-based snow-evolution system SnowModel and the Snow Microwave Radiative Transfer (SMRT) model, which characterizes microwave interactions with snow and ice. Together, these tools provide a powerful framework to improve the interpretation of radar altimetry signals, particularly in the Ku and Ka bands, which are central to current and upcoming satellite missions such as CryoSat-2, Sentinel-3, and CRISTAL.

The research builds on diverse datasets, including field measurements in Finland and Svalbard as well as international airborne sea-ice campaigns in the high Arctic with coordinated satellite underflights. Case studies of Arctic lake ice and sea ice will evaluate the consistency of model results against in situ data and study the influence of snow layering on radar signals. These insights will then be extended to seasonal and long-term analyses, enhancing our ability to detect and interpret climate-driven changes in the Arctic cryosphere.

Expected outcomes include improved algorithms for retrieving snow and ice thickness from satellite observations, validated modelling frameworks with wide applicability, and new understanding of how warming-induced changes in snow and ice affect satellite monitoring.

Authors: *Jakob Knieß, Paul Schattan, Franziska Koch and Karl-Friedrich Wetzel1*

A possible paradigm change in drone flight planning for faster acquisition in complex terrain - Leveraging existing potential in UAV based photogrammetry for snow depth mapping

Abstract:

Knowledge of spatio-temporal snow storage is crucial to understand snow-hydrological dynamics in complex, high alpine environments. Due to the low cost and fast deployability, photogrammetry in combination with commercial aerial photography UAVs has become a viable method for capturing high-resolution snowpack information. We utilize this technique in a high alpine catchment at Mt. Zugspitze in Germany to capture digital snow surface models and consequently snow depth information in heterogeneous environments. The fundamental step is the acquisition of overlapping aerial images, which are used for the reconstruction of the surface in the photogrammetric processing. It is well known that the properties of the image dataset determine the quality of the resulting reconstruction. Therefore, a number of studies from different areas of research focus on this topic. For snow depth mapping, Bühler et al. 2016 recommend, for instance a single overlap value, while Lee et al. 2021 collected different overlap values. Wu et al. 2025 found that the 3D model quality in an urban environment is linked to the overlap of an oblique image dataset in a nonlinear way. Depending on the studied terrain and structures, Maes 2025 summarizes various recommendations for appropriate overlap settings. To provide an insight into how often, in what resolution, and from which angle an area is captured, the current concept of overlap is unsuited. We suggest a paradigm change towards metrics representing the image information of a surface. Our approach is to increase the image capture frequency while angling the camera in a forward direction, wherefore a high image capture frequency of current digital camera systems is fundamental. Through this combination, the near-nadir information is retained, and the changed viewing geometry provides additional information in the along path and side view directions. The potential can be used for an increase in the dataset quality or a decrease in capture time. Both are highly relevant when working in the structurally complex and remote regions of high mountain areas. Battery capacity and regulations for flight speed and height do limit other options for an increase in data capture. Our goal is to share preliminary results for increasing the information in the image dataset while staying within the capability of current hardware.

Literature:

Bühler et al. 2016. https://doi.org/10.5194/tc-10-1075-2016

Lee et al. 2021. https://doi.org/10.3390/rs13040828

Maes 2025. https://doi.org/10.3390/rs17040606

Wu et al. 2025. https://doi.org/10.1016/j.conbuildmat.2025.142382

Authors: *Franziska Koch, Simon Gascoin, Korbinian Achmüller, Paul Schattan, Elias Bögl, Roberta Facchinetti, Jakob Knieß, Carolin Rempfer, Cesar Deschamps-Berger, Michael Lehning, Till Rehm, Karl-Friedrich Wetzel, Karsten Schulz, Christian Voigt*

Snow-hydrological contribution to signals from a superconducting gravimeter on top of Mount Zugspitze, European Alps

The understanding and quantification of the high-alpine water balance is very challenging. In particular, the estimation of the amount of snow and its spatiotemporal distribution in complex terrain is currently considered as one of the most important challenges in alpine hydrology. Since 2019, a superconducting gravimeter has been in operation at the Zugspitze Geodynamic Observatory Germany on top of a snow-dominated and karstified high-alpine site in the European Alps. Hydro-gravimetry is a non-invasive method of observing temporal gravity variations after the reduction of all other geophysical signals as the integral of all hydrological mass variations within an area of a few kilometre scale. The gravimetric signals include short-term, seasonal and long-term cryospheric and hydrological mass changes in a few kilometres scale radius. At this site, the seasonal snowpack variation has the largest impact on the gravimetric signal. The spatiotemporal gravimetric contribution of the snowpack was calculated applying a physically-based snowpack model including a satellite-based snow depth image derived by stereo photogrammetry for precipitation ad snow pattern scaling. The results show a high RMSE of 1.8 nm/s² between the observed and simulated snowpack gravity effect during the melt season. Besides disentangling the integral gravity information regarding the snowpack, also first results on snow-karst-hydrological modelling and estimates on diminishing ice storages will be presented in the context of high-alpine cryo-hydro-gravimetric monitoring.

Authors: *Andreas Kollert, Andreas Mayr, Simon Gascoin, Karl Hülber, Martin Rutzinger*

Assimilating soil temperature into the spatially-distributed snow model openAMUNDSEN

In recent years, data assimilation (i.e., integrating observed- with modeled data) has gained more and more attention in the hydroclimatological modeling community and is increasingly being used to improve modeled estimates of snow properties. Various kinds of remotely sensed and in-situ measured variables, such as snow depth, fractional snow cover, wet snow maps, as well as land surface temperature, were successfully assimilated into snow models. In contrast, near-surface soil temperature, which is strongly controlled by the presence and absence of snow cover, has largely been ignored for assimilation in snow models, despite its potential to improve estimates of such models. Therefore, the degree to which soil temperature measurements are able to improve modeled snow properties and whether they help to improve modeled snow properties at all, is largely unknown.

Here, we assimilate soil temperature measured at 10 cm depth in hourly intervals from approximately 900 measurement points on a single mountain into openAmundsen, a spatially-distributed hydroclimatological model. Data assimilation is performed using a particle batch smoother on a set of model runs with perturbed air temperature and precipitation. The model is run for the winter season 2022/2023 at hourly timesteps and 20 m spatial resolution. Results are evaluated against snow cover data derived from webcam and Sentinel-2 time series. We quantify how the assimilation affects snow-onset date, snow melt-out date and snow cover duration. Furthermore, we also assess if modeled soil temperature is improved by spatially propagating information from the data assimilation to modeled grid cells that were held back during data assimilation.

Authors: *Anton Komarov et. al*

Variations in Snow Properties and Stratigraphy Driven by the Urban Heat Island Effect in the Moscow Area

The urban heat island (UHI) effect results in higher temperatures in cities compared with nearby rural areas. While the urban heat island (UHI) phenomenon is well documented, its effects on snow cover properties remain insufficiently explored. In this study, we investigate the influence of the UHI on snowpack characteristics and stratigraphy by comparing an urban site (Moscow) and a nearby rural site (Khotkovo) over the 2014–2022 period. Our approach combines in-situ measurements of snow depth and density with meteorological station data on snow depth, temperature, and precipitation, as well as satellite-based land surface temperature observations from MODIS (MOD11A1). Results show that snow cover duration was shorter at the urban site due to later onset and earlier melt. Despite slightly higher winter precipitation in Moscow, snow depth and snow water equivalent were consistently lower than in Khotkovo. Urban snowpacks had higher average density. Stratigraphic analysis revealed thicker melt-freeze layers in Moscow and thinner layers of faceted crystals and depth hoar compared to the rural site.

Authors: *Kerttu Kouki, Andreas Colliander and Aku Riihelä*

Detecting rain-on-snow events using passive microwave satellite data

Rain-on-snow (ROS) events occur when liquid precipitation falls onto snowpack, leading to accelerated snowmelt and the formation of ice layers. These events decrease albedo, intensifying the snow-albedo feedback, and can trigger avalanches and increase flood risk due to the combined effects of rainfall and snowmelt. As climate change shifts precipitation patterns from snow to rain, ROS events are becoming more frequent and intense, making their accurate detection increasingly important. Passive microwave satellite data offer promising potential for detecting ROS events. However, most previous studies have focused on a limited number of frequency channels, typically 19 and 37 GHz. Recently, L-band (1.4 GHz) has gained attention, but a comprehensive evaluation across the full microwave spectrum is still lacking. This study aims to address this gap by assessing the suitability of multiple microwave channels for ROS detection. We analyze the feasibility of identifying ROS events using brightness temperature (Tb) data from the Soil Moisture Active Passive (SMAP) and Advanced Microwave Scanning Radiometer 2 (AMSR-2) satellites (1.4, 6.9, 10.7, 18.7, 23.8, and 36.5 GHz), evaluated against in situ observations. Additionally, we use the Snow Microwave Radiative Transfer (SMRT) model to simulate the impact of ROS events on Tb across a wide range of microwave frequencies. This combined modeling and observational approach aims to establish a robust framework for ROS detection. We focus on the Sodankylä region and cover the years 2015 to 2024. While the current focus is regional, the goal is to develop a method scalable to the broader Arctic. Preliminary results indicate strong potential for detecting ROS events using passive microwave observations. A distinct change in Tb is observed during ROS events, demonstrating the sensitivity of microwave observations to liquid water in the snowpack. SMRT simulations further support these findings. The final results of this study will include a comprehensive analysis of the feasibility and performance of the frequencies in detecting ROS events.

Authors: *Laurence Charbonneau, Daniel F. Nadeau, Vincent Vionnet, Marie Dumont and Kévin Fourteau*

Towards a better representation of the physical properties of Arctic snowpacks in the SVS2-Crocus model

Despite its importance for hydrological applications, Canada lacks a comprehensive understanding of snow water equivalent (SWE) distribution at large scales. The upcoming Terrestrial Snow Mass Mission satellite mission aims to address this gap by providing SWE mapping across the country at 500 m spatial resolution every 5 to 7 days. However, retrieving SWE from satellite backscatter coefficients requires reliable estimates of snowpack physical properties, particularly microstructure characteristics (density, specific surface area, etc.). The mission will rely on the SVS2-Crocus land surface model to simulate snow microstructure properties, but this model's accurate capacity across Canada's diverse environments remains uncertain. This project aims to enhance the representation of physical processes governing snow microstructure in SVS2-Crocus at the Canadian scale, focusing on one of the most extensive land cover types in the country, which is the Arctic tundra. As this project is in its early stages, this poster presentation provides an overview of the methodology that will be employed to achieve the research objectives. The research comprises three complementary phases. Firstly, controlled laboratory experiments will be conducted in cold chambers at Météo France Snow Research Center and at Université Laval's laboratory. Arctic-type snow cover (a well-sintered snow layer overlying a depth hoar layer) will be recreated in the cold chambers and will be placed under different temperature gradients. The importance of water vapor diffusion and the potential formation of convection will be quantified. These laboratory data will then be used to evaluate SVS2-Crocus under controlled conditions. Three progressive modelling approaches will be tested. These range from the simple implementation of water vapor fluxes, where flux divergence is compensated by deposition and sublimation processes, to the full integration of diffusive fluxes and, ideally, convective processes in snow. This will be carried out in close collaboration with the Snow Research Centre in France. Finally, model improvements will be validated using existing Arctic and subarctic observations from Bylot Island (73.15°N), Cambridge Bay (IVORI dataset, 69.11°N) and Umiujaq (56.56°N) in Canada. Additional data will be also collected at Cambridge Bay. The results of this study will help address a gap in Arctic snow modeling by accounting for vapor transport processes, typically absent from snow models despite their importance for Arctic snowpack properties.

Authors: *Hans Lievens, Isis Brangers, Hans-Peter Marshall, Jaron Vandenbroucke, Emma Tronquo, Devon Dunmire, Bert Cox, Jarne Van Mulders, Tobias Jonas, Francesca Carletti, Mathias Bavay, Gabrielle De Lannoy*

Sentinel-1 snow depth retrievals in mountainous regions, supported by tower-radar experiments

Seasonal snow in mountain ranges is an essential source of water. The monitoring of snow properties, such as snow depth or snow water equivalent (SWE), can benefit a range of applications, including water resource management and renewable energy production. A new promising remote sensing method for the monitoring of snow in mountain ranges uses Synthetic Aperture Radar (SAR) observations from the ESA and Copernicus Sentinel-1 satellite mission, which operates at C-band (5.4 GHz) frequency in dual-polarization (VV and VH). The Sentinel-1 snow depth retrievals have demonstrated accuracy at sub-kilometer resolution over mountainous regions, including the European Alps. However, despite promising retrieval results, the underlying scattering mechanisms of C-band microwave signals in snow are still not fully understood.

During recent years, multiple C-band tower radar experiments have been carried out, aimed at improving the understanding of C-band radar interactions with different types of snow and in different environmental conditions. Timeseries experiments covering multiple snow seasons were carried out at point locations in the Idaho Rocky Mountains (2021-2024) and in the Swiss Alps (2023-2025). Spatial transects were collected in colder snowpacks around Fairbanks, Alaska, during the March 2023 NASA SnowEx campaign.

The collected side-looking radar data consist of detailed time-domain profiles, revealing the scattering contributions of different snow layers and the soil surface. From the timeseries experiments it was observed that throughout dry snow accumulation, scattering from the snow volume increases over time. However, changes in scattering intensity can also partly be related to changes in snow microstructure and stratigraphy. The radar measurements in both co- and cross-polarization are impacted by dry snow accumulation, but impacts in cross-polarization are more strongly evidenced in the total measured backscatter, likely due to the relatively weaker reflection from the underlying soil. From the transects in the shallower and colder snowpack around Fairbanks, we observed that manual removal of the snowpack decreased the backscatter by 2 dB in all polarizations, supporting sensitivity of C-band data to snow and the potential use of Sentinel-1 to retrieve snow depth.

Authors: *Julio Miguel Lopez, David Pulido, Antonio Juan Collados, Jose Pedro Sánchez, Jesús Revuelto, Jose David Hidalgo, Juan Carlos García, Carlos Carnicero, Nemesio Heredia, Luis Carcavilla, Steven Fassnacht, Cesar Husillos and Arturo Jesus León*

Integration of in situ and remote sensing observations and machine learning for snow depth modeling in Sierra Nevada

Snow in mountain areas is a key resource for water management and associated ecosystems. In the context of climate change, marked by more frequent and intense droughts, it is necessary to quantify this resource in order to anticipate its availability and support management measures.

In Sierra Nevada (Spain), available snow depth data are limited and mainly based on point measurements using snow poles distributed across different locations. To expand this information base, several strategies have been implemented in recent years: (i) the collection of time series data through sensors installed on poles, and (ii) citizen participation through the submission of images of these poles.

Additionally, remote sensing techniques have been applied to cover larger areas. These include a LiDAR survey carried out by aircraft, a Pleiades satellite image, and drone-based photogrammetric surveys in the areas of Borreguiles, Hoya del Veleta, and Barranco de San Juan, in collaboration with the Aerial Works Service of IGME (STA) and the Pyrenean Institute of Ecology (IPE). Currently, new drone flights are being conducted to increase data availability, which are now in the processing stage.

The work carried out focuses on designing a methodology to use these data for training and calibrating a predictive snow depth model. This model incorporates spatially distributed topographic variables and the temporal variable Snow Covered Area (SCA), which provides the temporal variability needed for prediction. Using machine learning techniques, the model aims to characterize the spatial and temporal distribution of snow depth and to generate future estimates. In this way, it also seeks to analyze the relationship between snow dynamics and hydrological droughts.

Authors: *Juan Ignacio López Moreno*

Snow droughts in Australia

gutgitiutgiugtiugdasuyfuildi-jhñihgluidwq bvhjfyuwq

Authors: *López-Moreno, J.I.; Callow, N.; Vicente-Serrano, S.M.; Bilish, S.*

Changes in duration and intensity of snow droughts and their hydrological impacts in the Snowy Mountains (Australia)

This study presents a methodological approach to identify snow droughts and assess their influence on winter and spring runoff in the Snowy Mountains, Australia. For this purpose, we use weekly snow course data continuously collected since 1957 at three locations situated at 1463, 1615, and 1829 meters above sea level. Weekly Snow Water Equivalent (SWE) time series are standardized after being fitted to the probability distributions that best match their frequency. Snow droughts are then identified, and their intensity and temporal persistence are aggregated annually to detect long-term trends. Subsequently, weekly snow data are correlated with both observed and modeled hydrological records to identify the most critical periods and locations where snow droughts impact water availability.

Results indicate that snow droughts are becoming more intense and prolonged, particularly at lower elevation sites. This trend is primarily driven by a significant increase in temperature and a decrease in winter precipitation. These changes have negatively affected downstream water availability. Snow anomalies observed in late September and early October at higher elevations strongly influence runoff in October and November, explaining approximately 35% of the interannual variability in spring runoff. At lower elevations, snow accumulation in late August and early September shows the highest correlation with runoff during September and October, but has minimal influence thereafter. At 1400 m a.s.l., snow anomalies explain only about 15% of total spring runoff. Compared to SWE series, the Standardized Precipitation Index (SPI) appears to be the most significant driver of runoff variability and often offsets the impact of snow droughts on water availability.

Authors: *Bart?omiej Luks, Ekaterina Rets, Joanna Pluto-Kossakowska, Daniel K?pski, Adam Nawrot*

Assessment of Snow Depth in Fugleberget Catchment, Hornsund, Svalbard Using Terrestrial Laser Scanning and A-Melt Snowmelt Modeling

Accurate assessment of snow depth in polar regions is essential for understanding hydrological processes and predicting freshwater availability. This study investigates snowpack dynamics in the coastal, unglaciated Fuglebekken catchment near the Polish Polar Station in Hornsund, Svalbard, using high-resolution Terrestrial Laser Scanning (TLS) and snowmelt modeling. Data were collected as part of the WetSnowEx campaign under the HarSval project, which aims to enhance snow monitoring and melt modeling in Arctic environments.

TLS surveys were conducted during the snowmelt period in May and June 2024 using the Riegl VZ-6000 scanner, capturing detailed spatial variations in snow depth. These data were complemented by in situ measurements of snow depth and Snow Water Equivalent (SWE), as well as satellite imagery to assess snow cover extent. To simulate melt dynamics, the A-Melt model was applied, integrating TLS-derived snow depth data and meteorological inputs to estimate spatially distributed snowmelt rates.

While the analysis is ongoing, the integration of A-Melt simulations with observational datasets is expected to provide insights into the spatial variability of snowmelt processes and their relationship with topographic and microclimatic factors. Satellite imagery offers regional context, supporting interpretation of TLS and model outputs.

This study explores the potential of integrating TLS, in situ observations, remote sensing, and physically-based modeling (A-Melt) for comprehensive snowpack assessment in Arctic catchments. The combined approach is expected to enhance our understanding of snow distribution and melt dynamics, and to support future improvements in hydrological modeling and water resource management under changing climatic conditions.

Authors: *Jan Magnusson, Jens Oprel, Karoline Holand, Andreas Stordal, Gaute Lappegard*

SnowInflow: Optimized inflow forecasts for the snowmelt period

Norwegian hydropower plays a crucial role in the Nordic energy system, balancing variable renewable energy production in Northern Europe. Snowmelt contributes approximately to half of the inflow to Norwegian hydropower plants. However, optimally managing the reservoirs during the critical snowmelt period remains highly challenging due to substantial errors in snow amount estimates and predicted inflows.

In this contribution, we will provide an overview of the SnowInflow project financed by the Research Council of Norway. The project aims to improve inflow forecasts to Norwegian hydropower plants during the critical snowmelt period and is a collaboration between the hydropower company Statkraft (Oslo, Norway), the Norwegian Research Centre (NORCE, Bergen, Norway) and the WSL Institute for Snow and Avalanche Research SLF (Davos, Switzerland). In the project, we focus on three regions in South Norway, that contribute to roughly 5% of Norwegian electricity production. More reliable inflow forecasts during spring will improve hydropower scheduling in these regions, and better utilization of installed infrastructure.

The main research challenges of this project include (a) determining the optimal combination of ground and remote sensing observations for enhanced inflow forecasts, (b) developing physics-based snow models optimal for Nordic snow and climate conditions as well as for use in hydropower inflow forecasting tools, (c) creating automated data assimilation techniques for accurate incorporation of inflow and snow data, and (d) assessing the financial benefits of improving inflow forecasts using different snow measurements, modelling, and data assimilation methods.

We present an overview of ongoing measurement activities in the three study regions, including annual basin-wide snow depth lidar surveys and ground-based field campaigns. These datasets are used to enhance a physics-based snow model, which is evaluated against the operational temperature-index model (Shyft) currently applied in operational inflow forecasting at Statkraft and other hydropower companies. Beyond testing the physics-based model for more accurate snowmelt simulations, we also examine the added value of integrating lidar-derived snow depth data for improving snow and inflow forecasts. Finally, we demonstrate how automated data assimilation of runoff observations into the forecasting system leads to more reliable predictions and provides uncertainty estimates.

Authors: *Carlos Manso, Samuel Cirés, David Velázquez, Juan Ignacio López-Moreno, Eñaut Izaguirre, Ixeia Vidaller, Jesús Revuelto, Estela Nadal-Romero, Erik Cammeraat*

A tale of bacteria, viruses and snow: soil microbial diversity in the Pyrenean cryosphere

Microorganisms are crucial actors in shaping incipient soils in the mountain cryosphere. Within these fascinating extreme habitats, environmental factors like snow cover duration modulate not just microbial diversity but also essential ecosystem processes like biogeochemical cycling, bio-weathering, pathogenicity and antibiotic resistance. Advances in "-omics" approaches, particularly metagenomics, now provide unprecedented resolution for exploring microbial diversity, functional potential and ecological interactions. Here we present microbial metagenomic data from ongoing projects in soils of the Pyrenean cryosphere focusing on proglacial areas (Aneto Glacier) and subalpine environments (Izas Experimental Catchment) in Huesca, northeastern Spain. Our findings suggest an influence of snow cover duration on the diversity of soil microbial communities, their functional roles in carbon nitrogen, and sulphur cycling, and the ecological interactions between bacteria and viruses. These findings will be discussed in the context of the pioneering role of microorganisms in newly exposed soils, framed within the broader global trends of glacier retreat and declining snow cover in cryospheric regions worldwide.

Authors: *Emanuele Mariani, Fabian Wolfsperger, Carlo Marin, Barbara Cosciotti, Sebastian Emanuel Lauro, Elena Pettinelli and Elisabetta Mattei*

Laboratory characterization of snow dielectric properties using microwave probes

The dependence of snow's dielectric properties on parameters such as density and Liquid Water Content (LWC) makes its characterization essential for applications in remote sensing, hydrology, and snowpack modeling. In particular, the relative dielectric permittivity ?, considered as a complex quantity, is directly related to these parameters. To this end, it is essential to be able to perform laboratory measurements under controlled conditions. This paper presents the results of measurements carried out in climate chambers at the WSL - Institute for Snow and Avalanche Research - SLF laboratories on artificial snow samples with densities ranging from 100 kg/m3 to 550 kg/m3 and LWC between 0% and 13 %. The purpose of these measurements is to provide a dataset of dielectric permittivity values as snow parameters vary, to evaluate existing dielectric models in the literature. The density of the samples was controlled by varying the snow compression within a known volume, while the LWC was varied by mixing a known volume of water at 0°C with the snow. Complex permittivity estimates were performed using a transmission line connected to a Vector Network Analyzer (VNA) and terminated with an open-ended three-wires resonant probe. The resonances of the signal propagating along the line allow us to estimate the complex permittivity for frequencies between 200 MHz and 3.6 GHz. The experimental measurements of complex permittivity were subsequently compared with various models available in the literature. The results show that the Sihvola and Tiuri model, based on density and LWC values, provides permittivity values that are most in agreement with the measurements, both for the real ($R2 = 0.91$, RMSE = 0.23, bias = -0.80) and imaginary parts ($R2 = 0.85$, RMSE = 0.03, bias = 0.01), especially in the presence of LWC. In conclusion, this study has enabled the development of a laboratory measurement method for the dielectric properties of snow as density and LWC vary, providing a dataset with which to evaluate existing dielectric models in the literature and develop new, more accurate ones. The results support the interpretation of microwave remote sensing observations and offer a basis for improving snowpack modeling and water resource monitoring.

Authors: *Marie Dumont and Ghislain Picard*

What is the snow grain size? An historical perspective and an attempt for unification

The snow microstructure controls the properties of snow, for instance its optical, mechanical, thermal properties. The evolution of the snow microstructure is thus key to predict and analyze the evolution of snow for any applications. Simple scalar microstructure descriptors are thus needed in snow modelling or observations. The most used being, the snow density, closely followed by the snow grain size.

Defining a snow grain size for the porous material that is snow is however challenging. Indeed individual grains are not easy to identify. Several attempts have been made over the last decades, ranging from the maximal extent of individual grains to the more recent consensus of the specific surface area.

Here we will review these developments and make an attempt to provide a theory that unify them all, showing how this applies to the electromagnetic and optical properties of snow for modelling.

Authors: *Isabel Marín Beltrán, Javier Bandrés, Pablo Domínguez Aguilar, Jorge Pey, Jesús Revuelto and Juan Ignacio López Moreno*

Dark microplastics trigger changes on snow metamorphism that depend on snow initial density

Microplastic particles are ubiquitous contaminants present in every ecosystem, cryospheric regions being no exception. The presence of microplastics has been widely reported in polar regions as well as in glaciers and seasonal snow at mid-latitude mountain ranges. Still, their capacity to decrease snow albedo, change snowpack properties and trigger snowmelt, as light-absorbing impurities, remains understudied. During the snow season period of 2023/2024, six in situ experiments were conducted at the Spanish Pyrenees employing a set of mini-lysimeters and snow parcels containing surface snow aerosolised with different concentrations of dark microparticles. After 3 to 4 hours of exposition to microplastics, changes in albedo, snow specific surface area, liquid water content and the total melted water from natural snow samples were quantified. Results were very variable across the season, depending mostly on snow initial conditions. In the experiments performed after recent snowfalls (low snow density), increasing concentrations of microplastics yielded a clear decrease on snow specific surface area and albedo, and moderate increases in liquid water content and snowmelt. On the contrary, in the experiments performed on old snow with higher density (> 450 kg m-3), towards the end of the season, while changes on snow reflectance were smaller, an increase in liquid water content was observed in some of the samples, and effective (up to 65%) melting in all of them. Nonetheless, melting was observed also in the blank treatments and therefore was mostly attributed to meteorological conditions (warmer days and higher incident solar radiation). If microplastics were found at higher surface concentrations when there is an isothermal snowpack, and snow is exposed to strong energy inputs, during continuous periods, it is expected that they play a significant role in melting rates and earlier snowmelt. Assessing the interaction of microplastics with mineral dust, black carbon and microalgae is a future challenge for better snowpack modelling.

Authors: *Alejandro Martínez-Foronda and Luis Durán*

High-Density Snowpack Monitoring Through Temperature Profiling

Snow is highly variable in space and time, yet accurate measurements of its depth and water equivalent are essential for understanding key processes such as water supply, avalanche dynamics, and ecosystem functioning. Traditional manual methods are robust and inexpensive, but they are very human-demanding and limited in temporal density. In contrast, automatic sensors (e.g., ultrasonic or laser) are costly, infrastructure-dependent, and prone to operational issues. In this context, snow temperature profiling devices—commonly known as snow poles—offer a promising alternative, combining the simplicity of manual approaches with the temporal resolution of automated ones. Here, we present a novel method for retrieving snow depth from low-cost thermometric snow poles developed by our team, enhanced with recent advances in IoT hardware and communication technologies. The prototypes being tested allowed snowpack monitoring in complex mountain terrain with low cost, energy demand, and environmental impact. Laboratory sensitivity tests and preliminary field deployments demonstrate that the approach provides robust snow depth measurements and holds potential for deriving snow water equivalent. The method bridges the gap between traditional and modern monitoring strategies, providing an affordable and scalable tool for capturing the fine-scale variability of snow cover. This development may support improved hydrological forecasting, avalanche risk management, and ecosystem research in snow-dominated environments.

Authors: *Michael Matiu, Francesco Toldo, Filippo Di Marco, Diego Avesani, Bruno Majone*

From climate to streamflow: The role of multivariate bias adjustment and spatial downscaling on hydrological simulations in a mountainous region

The quantitative assessment of future water resources in mountain regions relies on climate model projections. These, however, need to be post-processed before they are fed into hydrological models. This post-processing often includes bias adjustment and downscaling techniques. Here we focus on two aspects, namely spatial versus point-based downscaling and univariate versus multivariate bias adjustment and test their impact on the full modelling chain by feeding climate model data into streamflow simulations across eight different watersheds in a mountainous region.

Climate data from reanalysis-driven regional climate models were bias adjusted and downscaled with different techniques to a 1 km grid for the Adige river basin in northeast Italy. Biases were assessed and compared along the whole modeling chain, from precipitation and temperature to snow and streamflow.

The multivariate bias adjustment enhanced streamflow simulations with respect to the univariate method, especially in high-altitude watersheds and in the winter season, suggesting that the correlation between temperature and precipitation has a significant impact on simulated snow cover. Moreover, the spatial downscaling method produced the best representation of precipitation and of streamflow. This highlights the crucial role of spatial coherence of precipitation input for hydrological modeling while downscaling climate variables.

Consequently, this study provides insight into best practices when using climate model data, post-processing, and hydrological simulation in mountain regions with complex terrain where snow is a key feature of the hydrological regime.

Authors: *Matthieu Lafaysse and Kévin Fourteau*

The daunting hurdles in snow modeling

Numerical snow models are widely used in the scientific community to understand physical processes within the snowpack, investigate bioclimatic interactions, or anticipate snow-related hazards in the short or long term. Although most users are familiar with the main features of the processes implemented in snow models, the numerical details of these schemes are often poorly understood and rarely scrutinized. This contribution discusses the reasons for this situation and the potential avenues or challenges for improving snow modelling. Firstly, identifying limitations requires a comprehensive description of hundreds of equations, which is challenging to convey through traditional scientific dissemination channels (publications, conferences). Secondly, several underestimated issues arise from the uncoupled solving of inherently coupled processes. Theoretical solutions to these issues often face obstacles due to the rigid structure of models, particularly when snow models are components of larger Land Surface Models, themselves coupled with Numerical Weather Prediction systems and/or Earth System Models. Finally, the computational cost of enhancing process descriptions is sometimes perceived as a limiting factor. However, objective and comparative analyses of the numerical costs associated with different processes and components of Land Surface Models are often unavailable to the community, hindering the development of targeted innovative solutions for the most computationally expensive components (numerical schemes with improved stability or emulation through artificial intelligence).

Authors: *Marco Mazzolini, Marianne Cowherd, Kristoffer Aalstad, Manuela Girotto, Esteban Alonso-González, Désirée Treichler.*

Gaussian Processes to optimize and accelerate Spatio-temporal Snow Data Assimilation

Spaceborne observations of snow depth are of great societal relevance because we can potentially use them to infer snow amounts even in remote mountains. However, such data are not currently used in snow reanalysis or forecasting because they are sparse in space and time. For example, the laser altimeter ICESat-2 often provides only one snow depth profile per snow season in a mountain catchment.

Data Assimilation (DA) uses information from snow observations to constrain snow models and provide gap-free distributed simulations. The assimilation of satellite image-based observations like fractional snow cover, typically in the melt season, is well established for reanalysis. However, sparse snow depth profile observations remain largely untapped. Assimilating snow depth observations in the accumulation season also holds the promise of improving snow forecasts.

Spatio-temporal DA has been adopted to spatially transfer information from observed locations to similar unobserved locations by modeling prior covariances as a function of topographical indices and the climatology of the melt-out date. In previous studies, we showed for a small catchment that these features are more relevant for determining snow similarity compared to more traditional geographical distance. However, the prior covariance model was fixed and controlled by a constant length scale hyperparameter. In this work, we exploit airborne lidar snow depth maps acquired by the Airborne Snow Observatory (ASO) in the East River basin in Colorado (USA), to optimize the similarity measure between simulated cells. For this, we use Gaussian Processes (GP), which offer a probabilistic approach to optimize the prior covariance function by inferring the importance of geographic, topographic and snow-climatology variables through a method called Automatic Relevance Determination (ARD).

A lingering challenge for spatio-temporal snow DA is the high computational cost of modelling large areas at high spatial resolution. We show that the GP analysis can also be used to iteratively determine a limited number of locations in a multi-dimensional feature space that are representative for the entire domain. This allows us to run the FSM2 model – with data assimilation – for a far smaller number of representative points in feature space, using the optimized covariance function to propagate the assimilated and modelled information to all cells in the geographical domain. In this work, we assimilate a snow depth profile extracted from ASO data, but the presented workflow is applicable to sparse snow information from ICESat-2 laser altimetry or other sensors that provide spatially incomplete information about snow.

Authors: *Giulia Mazzotti, Kate Hale, Simon Gascoin, Giulia Mazzotti, Michelle Hu, Anna Kontu, Steve Margulis, Joachim Meyer, Noah Molotch, Karl Rittger, McKenzie Skiles, Jack Tarricone*

Scientists' Warning on the Loss of Snow

Long term ground observations, remote sensing records, and Earth system modeling agree on the widespread decline of seasonal snow at regional to global scales. The loss of snow in a warming climate, which can partly be attributed to human action, threatens the large variety of resources and services to the environment and society snow provides. As we enter the United Nations' Decade of Action for the Cryospheric Sciences, shrinking glaciers and ice sheets are today well perceived as sentinels of climate change by the public and politicians, while the consequences of losing seasonal snow are often less realized by the same communities. Scientists' Warning on the Loss of Snow is a paper project led by Snow International (SINTER), an international community of snow scientists and enthusiasts. We bring together representatives of major international groups and organizations concerned with snow science to summarize the multifaceted value of seasonal snow, highlight the environmental, economic, and cultural cost of losing it, and call for action from the scientific community. The work will contribute to the Warning Articles' collection, an attempt from the Alliance of World Scientists to reach a broad audience and hopefully turn knowledge into action.

Authors: *Giulia Mazzotti, Kaja von Rotz, Louis Quéno, Marin Kneib, Matthias Huss, Moritz Oberrauch, Jan Magnusson, Tobias Jonas*

Towards improved estimates of high-elevation snow: combining processed-based snow modelling and glaciological datasets

Glacier surface mass balance is a pivotal descriptor of glacier evolution and thus a target variable of glacier monitoring efforts worldwide. Its accumulation component is tightly linked to the evolution of seasonal snow, which is shaped by complex processes. In particular, topography creates considerable variability in the meteorological drivers such as wind and solar radiation, leading to heterogeneous snow accumulation, redistribution, and melt patterns. Today, a number of physically-based models that can resolve these processes exist and are applied in snow research and operational snow monitoring efforts, yet these approaches are seldom used in glaciological contexts. At the same time, glacier datasets are rarely considered in snow modelling but could inform model adaptations specific to high-elevation areas, where their performance generally deteriorates. Here, we address this untapped potential for the case of Switzerland. Snow simulations obtained with physically-based modelling chains run by SLF's Operational Snow Hydrological Service (OSHD) are assessed against glacier mass balance data collected by Glacier Monitoring Switzerland (GLAMOS), aiming to identify snow mass biases and their spatiotemporal distribution. At the same time, glacier-wide mass balance estimates derived by interpolation of in-situ measurements are contrasted to simulated snow distribution patterns that better capture the underlying physical processes. By bringing together the two complementary approaches, we identify potential synergies that could be exploited to advance future cryospheric modelling with application in both snow and glacier mass balance monitoring.

Authors: *James McPhee, Diego Blanch, María Courard, Yerel Morales, Elizabeth Ramirez, Cristóbal Sardá, Paloma Palma, Tamara Muñoz, Noemí Villagra, Javiera Bustamante*

Snow hydrology in the mediterranean Andes Cordillera: insights from experimental catchments, remote sensing and numerical modeling

The combination of increased water use and the mounting evidence of cryosphere demise because of anthropogenic global warming has heightened public interest for monitoring, understanding, and predicting snow-driven streamflow originating in high mountain headwaters in the Andes Cordillera. Relatively unexplored compared to other major mountain systems in the world, the mediterranean Andes displays extreme topographic and climatological gradients a couple hundred km in the east-west, and approximately 1000 km in the north-south direction. Although satellite-based studies of snowcover evolution and trends are available for this region, multiscale snow hydrological process understanding remains incomplete due to the paucity of field-based research. In this work we analize in detail some processes that determine the hydrological response of snow-driven Andean watersheds, through the combination of intensive field campaigns and sensor networks located in experimental catchments, remotely sensed snow cover and depth, and snowdrift-permitting, and uncalibrated physically-based numerical simulations. Preliminary results indicate the importance of gravitational redistribution, highlight the difficulties in estimating appropriate wind fields for blowing snow estimation, and suggest that existing parameterizations may underestimate albedo decay and melt rates during the winter-to-spring season transition. Future directions in monitoring and process characterization are suggested in concordance with the Decade for Action on the Cryospheric Sciences.

Authors: *Adrián Melón Nava*

A Multi-Satellite Approach to Snow Monitoring in the Cantabrian Mountains Using Google Earth Engine

Snow cover plays a crucial role in the hydrology and climate of mountain environments, regulating water availability and influencing ecosystem and geomorphological dynamics. In the Cantabrian Mountains (northern Spain), snow monitoring is particularly challenging due to the scarcity of long-term ground observations. This work presents a 23-year assessment (2000–2023) of snow-cover dynamics using MODIS, Landsat (5–8), and Sentinel-2 imagery processed within the Google Earth Engine (GEE) platform.

A total of 10,831 satellite images were filtered and processed to generate a daily snow-cover collection. Snow presence was determined through the Normalized Difference Snow Index (NDSI) for Landsat and Sentinel-2, and Fractional Snow Cover (FSC > 0.15) for MODIS. Cloud-induced data gaps were filled using a temporal interpolation method (up to 5 days). From this dataset, indicators such as Snow-Cover Days (SCDs) and Snow-Cover Fraction (SCF) were derived to characterize spatial and temporal patterns and trends.

Results reveal pronounced spatial and altitudinal variability, with an average of 30 snow days per year, increasing from less than 10 days below 500 m to more than 130 days above 2000 m a.s.l. Trend analysis indicates a general decline of ?0.26 days per year (?0.92 days per year in significant areas), especially between 1500–2000 m. SCF records show marked interannual variability, with maximum snow extent typically observed in late January to early February and below-average seasons after 2018–2019.

This study demonstrates the potential of GEE-based multi-satellite integration for continuous, long-term monitoring of snow dynamics in data-scarce mountain regions, providing valuable insights into the impacts of regional climate variability on snow persistence.

Authors: *Adrián Melón Nava and Amelia Gómez Villar*

Variability of Snow Cover in the Cantabrian Mountains, Spain: A Multi-Watershed Satellite-Based Analysis from 2000 to 2024

This study presents a comprehensive analysis of snow cover variability in the Cantabrian Mountains (northern Spain) from 2000 to 2024, using over 14,000 multi-sensor satellite images processed via Google Earth Engine. The analysis encompasses 36 hydrographic watersheds divided into 500-meter elevation bands to evaluate snow cover extent, duration, persistence, and seasonal snow phenology.

Results reveal significant reductions in snow cover extent, particularly during winter, with declines of up to 16% per decade in some watersheds above 1,500 meters, most notably on south-facing slopes. Autumn snow cover also decreased by approximately 2% per decade above 1,500 meters, while spring snow cover remained largely stable except for marked reductions above 2,000 meters. The snow season is shortening mainly due to earlier snowmelt; the last ephemeral snow day (LESD) advances by 2.7 days per decade, whereas the first ephemeral snow day (FESD) shows only a slight advance. The duration of the first snow cover episode has decreased by 9 days per decade above 1,500 meters, and the longest snow cover duration has shortened by up to 8 days per decade above 2,000 meters—the elevation range where ski resorts are located. Peak snow cover dates tend to occur slightly later but with reduced persistence at higher elevations, while at lower elevations, peak snow cover is shifting earlier by several days per decade.

Snow cover persistence, expressed as the ratio of snow duration to the total snow season length, exhibits a declining trend, especially above 1,500 meters, indicating increasingly unstable and intermittent snow conditions. These changes have critical implications for regional hydrology, alpine ecosystems, and winter tourism, all of which depend on sustained snow cover.

Despite inherent limitations due to cloud cover, canopy effects, and rapid melt events that may elude satellite detection, the findings provide robust evidence of a consistent trend toward reduced snow extent, duration, and stability over the past two decades. This underscores the urgent need for continued long-term monitoring and integration with ground-based observations to better understand climate-driven snow dynamics in this mountainous region.

Authors: *Adrián Melón Nava and Javier Santos González*

Evaluating Satellite Snow Cover Detection Using Time-Lapse Cameras in Northern Spain

Monitoring snow cover from space in mid-latitude mountain regions remains challenging due to cloud cover, topographic complexity, and limited revisit frequency of optical satellites. To assess the reliability of satellite-based snow detection, this study compares over 99,000 time-lapse camera images (2003–2025) with coincident snow-cover observations from MODIS, Landsat (5–9), and Sentinel-2 across the Cantabrian Mountains and Sierra de la Demanda (northern Spain).

Results show that cloud cover obscured up to 57% of satellite acquisitions, increasing the effective revisit interval to 2.3 days for MODIS, 6.9 for Sentinel-2, and over 21 days for Landsat. A multi-sensor approach combining all datasets within Google Earth Engine and applying a 5-day gap-filling interpolation reduced this to 1.3 days.

When compared to camera records, satellites underestimated snow presence by 61–80%, primarily due to cloud obstruction. However, when both records provided cloud-free observations, classification agreement exceeded 85%, confirming that the discrepancy lies mainly in data availability rather than algorithmic misclassification.

Satellite-derived Snow Onset (SOD) and Snow Melt-Out Dates (SMOD) were also biased, with onset dates detected 13–52 days later and melt-out differing by up to 40 days compared to camera-based timelines. These discrepancies highlight the limitations of optical satellites for detecting ephemeral snow events in cloudy mountain environments.

The integration of ground-based time-lapse imagery and multi-sensor satellite data improves snow season characterization and offers a practical framework for validating and enhancing satellite snow monitoring in mid-latitude mountain regions.

Authors: *Joachim Meyer, Andrew Hedrick, Hans-Peter Marshall*

Inferring precipitation information from multi-year aerial snow depth observations to improve snow energy balance model inputs

The snow dominated headwaters in the mountains of the Western United States (US) are an essential seasonal water resource. Predicting the spring release timing and magnitude requires accurate spatial information of snow distribution and extent during the accumulation and ablation seasons. One way of trying to capture the accumulation phase of seasonal snow is through the use of spatially distributed snow energy and mass balance models that simulate the snowpack from meteorological observations. One of the dominant inputs that dictates a model's ability to accurately simulate snow cover is precipitation, which to date is either recorded through sparse in-situ measurements stations or modeled with coarser scale numerical weather prediction models (NWP). The NWP models are initialized with spatial or point observations that often have limited coverage in mountain areas, leading to underestimation or missing areas of snowfall. Approaches to improve the quality of precipitation include the use of spatial snow depth distribution patterns to inform precipitation/snowfall estimation, correcting the homogeneous precipitation outputs of standard interpolation methods with measured accumulation patterns. The number of spatial snow depth observations have increased over the recent years, with lidar-based platforms dominating the underlying technology. In this work, we evaluate the use of snow distribution maps along with bias correction from in situ point observations to inform the precipitation input of the spatially distributed iSnobal snow energy and mass balance model to improve simulated snow depth accuracy. The lidar-based depth maps were recorded over multiple winter seasons (2020 - 2025) in Mores Creek, Idaho, US, and capture a range of accumulation seasons from below to above average years. Normalization across flights during the accumulation period showed a promising potential to derive precipitation information that can be used across water years to reduce the need for repeated observations and enhance the scalability of this approach.

Authors: *Noah Molotch, Patrick Saylor, Alice Hill, Thomas Painter, Charles Miller*

Atmospheric transport of light-absorbing impurities across the Tasman Sea: Hyperspectral insights into bushfire and dust impacts on New Zealand glaciers

The deposition of Light-Absorbing Particles (LAP) onto high elevation glaciers is a critical phenomenon with respect to snow and ice albedo and energy fluxes. During late 2019 and early 2020, intense plumes of wildfire-related dust, soot, and black carbon were transported from record Australian bushfires across the Tasman Sea, depositing high concentrations of LAP's onto mountain glaciers across the South Island of New Zealand. This research uses hyperspectral space-borne data collected from the Agenzia Spaziale Italiana (ASI) PRISMA (PRecursore IperSpettrale della Missione Applicativa) sensor in tandem with the Two-StreAm Radiative TransfEr in Snow (TARTES) snow spectral model to estimate the magnitude of this unique LAP deposition event on the Cascade glacier, Southern Alps, New Zealand. We estimated concentrations of LAPs on the surface of the glacier, determine the commensurate snow-darkening in contrast to modeled clean snow surfaces, and estimate the radiative forcing (RF) of the LAP's. In this regard, we estimate an average optically-equivalent snow grain radius of 721 +/- 42 µm. Within the visible portion of the electromagnetic spectrum (350-750 nm), we estimate an average albedo decrease of 0.07 +/- 0.01, illustrating a 12% mean reduction over the visible spectrum. The largest decrease in spectral albedo is observed in the visible portin of the spectrum between 350-750 nm - consistent with high concentrations of LAP's. The radiative forcing commensurate with the LAP concentrations was estimated as 169 W / square meter. The unique contribution of this study lies in the demonstration of the high LAP concentrations associated with long-range regional transport. In addition, the research illustrates the unique capabilities of satellite-based hyperspectral measurements in the quantification and attribution of LAP with regard to snow and ice energy balance and, implicitly, mass balance.

Authors: *Moritz Oberrauch, Bertrand Cluzet, Jan Magnusson, Tobias Jonas*

Improving distributed snowpack estimates in complex terrain through the joint assimilation of in situ and spaceborne snow observation

Monitoring snow water equivalent in mountainous regions is essential for managing water resources and mitigating natural hazards, but it is especially challenging due to the complex terrain. Snowpack observations typically provide either frequent temporal sampling or broad spatial coverage, but rarely both, while numerical models represent both dimensions but remain inherently uncertain. Data assimilation combines these two sources of information into an updated estimate and is increasingly used within operational snow hydrological applications. However, transferring information from spatially sparse in situ observations or temporally infrequent remote sensing observations may have limited value if the observations are not representative of the unmonitored conditions.

We show that the information content of point-based snow depth observations from a network of monitoring sites allows for correcting spatiotemporal error patterns in the model forcing data at subregional scales. Using a particle filter to infer local forcing corrections and then interpolating them to unobserved locations improves snowpack estimates across the entire domain. Nonetheless, the spatial representativeness of observations from flat and open-field sites sets an upper limit to the performance of the assimilation scheme, particularly in steep complex terrain. Simply assimilating more observations from additional sites or adopting a more sophisticated assimilation scheme yields diminishing returns, and uncertainties in model predictions at slope scales remain unaddressed.

Spaceborne observations of fractional snow cover offer additional spatially explicit information, though at irregular and infrequent intervals. By assimilating this data into an ensemble of fully distributed simulations, we can adjust model parameters related to processes sensitive to slope, aspect, and other terrain features, thereby enhancing snowpack estimates at much smaller scales. The joint assimilation of both in situ and remote sensing observations provides an opportunity to leverage the complementary information from both data sources to improve operational snow hydrological nowcasting applications beyond the removal of subregional biases.

Authors: *Thomas H Painter, Kat J Bormann, Jillian Gaylor, Cara Piske, and Jeff Deems*

An assessment of SWE reconstructions and interpolations with Airborne Snow Observatory data

Across the last several decades, the snow hydrologic and cryosphere communities have worked toward mapping snow water equivalent across mountain basins. For airborne and spaceborne efforts, radar with various frequencies have been attempted with suggested support from in situ measurements and empirical insights. Unfortunately, these attempted retrievals have continued to struggle due to liquid water in the snowpack, textural and layering discontinuities in the snowpack, and liquid water in vegetation.

In the 1990s, the concept of SWE reconstruction commenced with reverse time series of remotely sensed snow covered area and available gridded energy fluxes. Through what one colleague described as "GIS calorimetry", SWE was draped onto the landscape to an approximate peak SWE. Several research groups have created such products based on Landsat/Sentinel-2 multispectral data with its relatively temporally sparse time series to the more temporally dense but spatially coarser MODIS multispectral data, all built upon fractional fSCA retrievals from the SCAG concept and subsequent derivatives. These products continue to be generated and made available publicly.

In 2013, the NASA/JPL Airborne Snow Observatory first plucked the "holy grail" of snow hydrology by first mapping SWE across mountain basins with high accuracy and precision with scanning lidar, imaging spectrometer, and physical modeling. Until the advent of the Airborne Snow Observatory, the accuracy and precision of SWE reconstructions were simply not known. Since, a few investigators have assessed these SWE reconstructions with ASO and its follow-on Airborne Snow Observatories, Inc. datasets but only with data in the Tuolumne River Basin of California. This despite ASO Inc. now flying in 30 more basins across the Western United States.

In this presentation, we perform a broad assessment of SWE reconstructions and their vulnerabilities when used in science and water management. Early results indicate that SWE reconstructions have strong interannual, basin-to-basin, and subbasin spatial variability in terms of accuracy and precision. As such, their use in scientific studies and suggestions of use in water management should be treated guardedly and with abundant transparency as to these issues.

Authors: *Hotaek Park, Kazuyoshi Suzuki and Steven R. Fassnacht*

Depth hoar impacts on permafrost and greenhouse gas fluxes

Snow insulation significantly affects permafrost temperature, then feedback to ecohydrology and climate. Depth hoar is a physical process that often has a low thermal conductivity, strongly contributing to the snowpack thermal insulation and impacting the permafrost thermal regime. The formation of depth hoar in snowpack likely reduces permafrost cooling during the winter season, and then which could be fed back to greenhouse gas (CO_2 and CH_4) fluxes from the permafrost soil during the next growing season. Observations and models have provided little quantitative assessments on the impact of depth hoar on permafrost temperature and the associated feedback. To address this deficiency, we coupled the depth hoar process to the land surface model CHANGE and validated the model performance against observed data from arctic tundra (Tiksi: 71.4°N, 128.5°E) and subarctic boreal forest (Yakutsk: 62.15°N, 129.14°E) sites, underlaid by continuous permafrost. The simulated permafrost soil temperature showed good agreements with the observed seasonal and interannual variability at the two sites. The depth hoar-induced permafrost soil warming resulted in larger CO_2 efflux (i.e., respiration) from the permafrost soil while lower CH_4 production from dried soil, compared to model results excluded the depth hoar. These results suggest that the depth hoar-enhanced soil respiration through permafrost warming in the boreal forest and tundra sites. The depth hoar process is not represented in land surface models yet, highlighting the need for this model improvement and uncertainty assessment for the model simulations.

Authors: *Dmitry Pershin, Daniel F. Nadeau, Michel Baraër, Pierre-Erik Isabelle, Benjamin Bouchard*

Snowpack Energy Exchange During Rain-on-Snow Events in Boreal Environments of Eastern Canada

Rain-on-snow (ROS) events are becoming increasingly frequent in seasonally snow-covered regions worldwide. While extreme ROS can trigger catastrophic flooding through enhanced snowmelt, even moderate events alter snow stratigraphy and initiate localized melt, thereby influencing seasonal snowpack evolution. ROS dynamics are largely governed by the snowpack energy balance, which determines the availability of energy for snowmelt. However, the relative contributions of individual energy fluxes, their seasonal variability, and their magnitude across ecosystems remain understudied, largely because direct flux measurements are challenging.

In this study, we analyze the energy dynamics during ROS events based on detailed field observations across multiple environments in the boreal forest of eastern Canada (47° N, 71° W). Our sites range from clear-cut areas to dense forest stands, where we combined direct flux measurements with estimation methods based on canopy structure. The energy balance was evaluated using measurements of shortwave and longwave radiation, vertical snowpack temperature profiles (to quantify snowpack cold content), ground heat flux, and rare turbulent flux measurements obtained with a closed-path eddy-covariance system, which performs reliably during rainfall.

Over two winters (2023–2025), 20 ROS events with rainfall > 5 mm on established snow cover were recorded. Average rainfall was 20.5 mm, with two events exceeding 50 mm. During ROS events, net radiation, turbulent fluxes, and ground heat flux were consistently positive and directed toward the snowpack. Their magnitudes were relatively constant across the winter, regardless of whether ROS occurred early or late in the season, with some exceptions during prolonged storms. At the clear-cut site, turbulent fluxes dominated, contributing around 50% of the total energy inputs, while net radiation accounted for about 30%, mainly from the longwave component. In contrast, under forest canopies wind suppression reduced the role of turbulent exchange and enhanced the contribution of longwave radiation. Relative contributions of the different fluxes remained broadly stable across the season, except for a stronger ground heat flux during early-winter ROS. For most events, the available energy was sufficient to fully eliminate snowpack cold content.

Accurate quantification of energy exchange components during ROS will advance our ability to evaluate snow mass balance changes, partition rainfall and snowmelt contributions across boreal environments, and provide a stronger basis for testing and improving snow and hydrological models.

Authors: *Jorge Pey, Isabel Marín Beltrán, Juan Ignacio López Moreno, Javier Bandrés, Ramón Larramendi*

Presence and Potential Sources of Snow Impurities Along a Greenland Ice Sheet Gradient from the WindSled Expedition

This work presents coordinated field and laboratory protocols designed for the collection and analysis of snow samples in polar environments, with a focus on aerosol contamination and microplastics (MPs). Sampling was conducted across eleven sites along a traverse in Greenland, with duplicate samples taken from surface snow and approximately 30 cm depth to assess both atmospheric deposition and subsurface accumulation.

Fieldwork procedures emphasized contamination prevention and standardized sample collection. Snow was collected within delimited areas (30×30 to 40×40 cm). For the MPs samples, a dedicated procedure was used: pre-cleaned aluminum bottles and stainless-steel tools, ensuring minimal plastic contact. Samples were compacted to maximize volume and labeled systematically (e.g., GR1.1 for surface, GR1.2 for depth). Each sample pair was complemented by control blanks to account for airborne contamination.

At the end of the campaign, in the laboratory, aerosol and MPs samples were melted and filtered using stainless-steel vacuum filtration systems. Separate workflows were applied for aerosol and MP analyses. For aerosols, filtrate volumes were measured and aliquots preserved in 100 mL bottles, and insoluble aerosols were retained in quartz microfiber filters; for MPs, polyethersulfone filters were used for later microscopic and spectroscopic identification. Together, these protocols enable reliable quantification of microplastic and aerosol particles in snow, contributing to a standardized methodology for assessing atmospheric deposition of anthropogenic pollutants in remote cryospheric regions such as Greenland.

Results display interesting variability along the Greenland gradient, with non-negligible aerosol and MP concentrations at some sites. The exploration of the results with source apportionment models will provide valuable insights regarding atmospheric pollution reaching pristine polar environments.

Keywords: microplastics, snow sampling, Greenland, atmospheric deposition, cryosphere, contamination control, sources.

Authors: *Rafael Pimentel, Javier Aparicio, María José Polo*

Improving the understanding of the snow-streamflow nexus as the basis for a hydrological forecasting system in regulated Mediterranean mountains catchments

The socioeconomic development of Mediterranean mountain areas is directly linked to their snow-water resources. In addition, these areas possess high climatic variability, making torrential and drought events recurrent in these areas. During the last century, reservoirs have been built to deal with this variability, storing water during water-reach periods and using it during scarcity situations. However, managing these types of systems requires not only specific operating conditions of the infrastructure (e.g., minimum and maximum flow rates to be turbined depending on the available hydraulic machines), but also limitations related to the various uses of stored water, drinking water, irrigation, or environmental flows. Specifically, the spring period is the key timing for forecasting summer water resources, which, in general, are more prone to suffering from scarcity.

This work aims to enhance the understanding of the snow-streamflow nexus as the basis for the definition of a streamflow forecasting system based on antecedent snow-related variables. Spring melting cycles from 2001 to 2021have been chosen for this analysis. Two catchments in the Sierra Nevada Mountain Range (southern Spain), which drain into two reservoirs, Rules and Canales, are the two cases studied.

Two data sources are used for defining the nexus. On the one hand, the snow cover area in the catchment, which is retrieved from an improved data set created by combining Landsat, Sentinel, and MODIS products, is employed. On the other hand, the in-situ inflows to both dams are used for characterizing the streamflow dynamics. We want to predict four key variables for the dam manager: (i) the velocity of melting, (ii) the recession of streamflow, (iii) the maximum spring streamflow reached, and (iv) the number of days between the beginning of the melting and the time when spring flow is reached. For that, we use variables that can be monitored in advance, such as the maximum snow cover extent, the precipitation, and the snowfall accumulated until the beginning of the melting.

The results indicate that precipitation up to the onset of melting and the maximum snow surface reached in the year are the best predictors of spring melting and summer streamflow recession, with relative errors that range from -5% to 15% over the years. When using the relations found to predict, the errors were about 10%, proving the validity of the methodology proposed and constituting the basis of a forecasting system in the area.

Authors: *María José Polo, María José Pérez-Palazón, Rafael Pimentel*

Six decades of snowfall trends in Sierra Nevada Mountain range: spatiotemporal analysis

Sierra Nevada, a mountain range in southern Spain, is a clear example of a "snow island". That is, a small-sized snow area at the global scale in an eminently semi-arid region, which at the local scale plays a key role in water resources availability for lowland areas. This peculiarity increases due to its steep topographic gradient and its proximity to the Mediterranean Sea, which makes Sierra Nevada a unique environment. Therefore, this area can be used as a living lab, where observed changes can help to foresees future changes in snow-dependent areas located at higher latitudes.

In this context, this study aims to analyze the trends in snowfall patterns at different temporal scales during the last six decades in the Sierra Nevada Mountain Range. For this, ground precipitation and temperature measurements in more than 60 weather stations are utilized. This punctual information is extended to the whole Sierra Nevada Mountain Range by using spatial interpolation algorithms, which consider topographic gradient and orographic differences, and were already tested in the area. When interpolated, snowfall is computed using a zero-degree threshold. Snowfall is aggregated at different spatial (headwater catchments) and temporal (month, year, decade) scales, and trends are computed. The significance of these trends is evaluated using the Mann-Kendall monotonic test.

The results demonstrate the lack of parallelism between trends in precipitation and snowfall. A general increase in snowfall torrentiality - understood as the concentration of snowfall in a certain period (season, year, or decade) – along with an increase in aridity in some of the defined catchments, were found. In addition, we were able to identify different "nivo-types" connected to snowfall changes. These "nivo-types" are determined by the interaction of two marked spatial gradients beyond the topographical ones: north-south, with and without influence from the proximity of the sea and the subtropical climate of the Mediterranean coast in this area (among other processes), and west-east, with the decreasing influence of Atlantic storms (among other processes as well).

Authors: *John Pomeroy*

Prospects and Opportunities for Advancing Snow Hydrology in the Decade of Action for Cryospheric Sciences

Snow hydrology has made tremendous advances in the last 50 years, moving from an incomplete understanding of snow redistribution, sublimation, energetics, chemistry, ecology, and ablation processes, via novel observation techniques, satellite, and field campaigns, to a more complete understanding that is being matched by physically based high-resolution models. However, major areas of potential advance remain. This talk addresses the prospects and opportunities for improving snow process understanding, parameterisation, and prediction.

Advection of latent and sensible heat from bare ground or open water to snow is not fully understood. Alpine blowing snow calculations do not fully consider the role of terrain roughness and sparse vegetation on transport fluxes and atmospheric exchanges. Wind flow calculations in steep alpine terrain are still problematic and incapable of reliable estimation of wind speed and direction. Intercepted snow calculations lack an understanding of wind erosion and redistribution from forest canopies. Snow avalanche calculations used in hydrology are highly empirical and tuned to regional observations, so lack the global robustness of physically based methods. Snow water equivalent observations still depend on gravimetric methods and lack reliable high-resolution remote sensing approaches. Snowfall measurements are too sparse and in windswept terrain are still highly uncertain due to wind-induced undercatch and other gauge errors. Albedo impacts from atmospheric deposition on snow and biological magnifiers such as snow algae are understood but not incorporated in calculations. The role of edge effects such as treelines, glacier edges, canopy gaps and ridges on upscaled hydrological responses are incompletely understood. And what fine-scale processes are emergent or are compensated for in larger-scale energy and water budget calculations is not fully understood. Snow hydrology model performance is sometimes limited by sparse observations and coarse resolution forcing data that lacks the realism needed to force all snow process calculations. New research and coordinated global field and modelling campaigns are needed to solve the remaining uncertainties. This can be done as part of the UN's new Decade of Action for Cryospheric Sciences 2025-2034.

Authors: *Louis Quéno, Giulia Mazzotti, Jan Magnusson, Tobias Zolles and Tobias Jonas*

Including snow redistribution in snow hydrology modelling: bridging the gap from research to operational modelling at nation-scale

In mountains, wind- and gravity-driven transport of snow affects the overall distribution of snow and can have a significant effect on snowmelt dynamics. In the context of the Swiss operational snow melt forecasting, a compromise must be found to enable the representation of such small-scale processes over the entire Swiss Alps while maintaining viable computational costs.

To this end, the snow redistribution modules SNOWTRAN-3D and SnowSlide were implemented and adapted within the FSM2oshd physics-based snow cover model. In an earlier study we showed the added value of snow redistribution representations on a 1180 km2 domain within the Eastern Swiss Alps when running simulations at 25, 50 and 100 m spatial resolutions. Here, we present the challenges and developments that were needed to apply this research model successfully over the whole Swiss Alps at 100 m resolution in an operational setting. In particular, we discuss the following issues:

- The Swiss Alps include very high elevations, with summits above 4000 m.a.s.l. and glaciers. Transport parameters that were shown to be suitable for terrain at 2500 m.a.s.l. were not applicable in more extreme conditions and needed diversification.

- Wind fields, although dynamically downscaled, needed further post-processing to mitigate biases that became evident in comparison to wind station measurements, particularly on exposed ridges.

- The representation of snow redistribution and of forest snow processes had to be integrated as both types of processes coexist wherever open alpine terrain interfaces with subalpine forest.

- The snow cover fraction scheme had to be adapted to better account for snow transport processes and sub-grid variability in simulations at high spatial resolution.

Authors: *Claudia Ravasio, Giacomo Traversa, Roberto Garzonio, Olga Gatti, Paolo Pogliotti, Sepehr Norouzi, Carlo De Michele, Stefania Gilardoni, Leon Roussel, Roberto Colombo, Biagio Di Mauro.*

Radiative impact of mineral dust during the melting season at Plateau Rosa and Cime Bianche (Aosta Valley, Pennine Alps)

The cryosphere plays a central role in the Earth's climate system and serves as a sensitive indicator of climate variability. Multi- and hyperspectral remote sensing data provide a powerful means to retrieve snow and ice properties, including parameters related to the occurrence of Light-Absorbing Particles (LAPs). By reducing surface albedo, LAPs enhance the snow-albedo feedback, thereby altering the timing and magnitude of snowmelt and affecting water availability, with significant consequences for ecosystems and human communities.

In this study, we investigate the impact of Saharan mineral dust deposition on seasonal snow cover at the experimental sites of Plateau Rosa and Cime Bianche (Pennine Alps) by integrating multi- and hyperspectral remote sensing data, modelling, and field observations. We focused on the retrieval and validation of multiple snow parameters (e.g. snow grain size, broadband albedo, dust concentration, liquid water content (LWC), and instantaneous radiative forcing (iRF)) using hyperspectral data from the PRISMA mission, combined with radiative transfer modelling and field measurements, including snow reflectance, density, LWC, grain size, and dust concentration. Key snow properties were retrieved from PRISMA using a supervised machine learning approach based on the K-Nearest Neighbors (KNN) algorithm, enabling efficient mapping of snow characteristics across the study area, with results showing good agreement with in-situ observations. Furthermore, Sentinel-2 imagery was used to monitor spatial and temporal patterns of dust deposition and to estimate its radiative impact on the snowpack. Estimated iRF reached up to 200 W m?² during the 2024 melting season. Finally, we used remote sensing and field data as assimilation sources for the HyS2.0 Snowpack Model, which was advanced to a full energy-budget formulation. Using this model, we assessed the influence of LAPs on snowpack dynamics, including snow depth, snow water equivalent (SWE), density, and runoff, by quantifying their impact on surface albedo and snow temperature. Preliminary results predicted earlier melt-out dates (up to 8–9 days) in years with high dust load.

Our results highlight the importance of combining remote sensing, field validation, and physically based modelling to address challenges in snow parameter retrieval. This integrated approach provides detailed insights into the effects of LAPs on snow dynamics and their influence on seasonal streamflow, ultimately improving our understanding of climate feedback mechanisms in dust-affected alpine environments.

Authors: *Jesús Revuelto, Eñaut Izagirre, Francisco Rojas-Heredia, Ixeia Vidaller, Ibai Rico, Alfredo Serreta, Pierre René, Juan Ignacio López-Moreno López-Moreno*

Pyrenean Glacier Retreat and its relation with snow distribution: Insights from UAV

Pyrenean glaciers, like glaciers around the world, are highly threatened by climate change, and their disappearance is expected within a matter of years. This extreme vulnerability has likely increased both social and scientific interest in their evolution, motivating significant monitoring efforts. Thanks to the emergence of Unmanned Aerial Vehicles (UAVs), a high spatial resolution database of glacier retreat in the Pyrenees has been developed over the past five years. These observations are conducted annually—and in some cases twice a year, to capture maximum snow accumulation. Combined with other data such as ground surface temperatures and hourly melt dynamics at specific locations, these records offer a deeper understanding of glacier retreat in the Pyrenees. This work presents an update on glacier conservation in this mountain range, analyzing how snow cover influences their evolution. It also provides insights into their transition to new paraglacial stages, marked by increased debris cover and permafrost degradation.

Authors: *Alvaro Robledano, Matthew Olson, Joachim Meyer, J. Michelle Hu and McKenzie Skiles*

Recent iSnobal model enhancements: Assessing improvements from an updated representation of the radiative balance in the Upper Colorado River Basin (USA)

Across the western United States, seasonal snow is a critical water resource, and operational snow models are increasingly being enhanced to incorporate real-time forecasts for improved water management. The ability of iSnobal, a process-based spatially distributed snow model, to represent snow mass and energy balance has been demonstrated when forced with meteorological inputs from the High-Resolution Rapid Refresh (HRRR) numerical weather prediction model, supporting its potential for operational use. In this work, we present additional enhancements to the radiative balance of the iSnobal model. Traditionally, incoming solar and longwave radiation were theoretical clear-sky maximums, modulated by topography, cloud cover and vegetation. Net solar radiation was computed using a time-based albedo decay curve due to sparsely available in situ measurements. In this work, the incoming solar and longwave radiation schemes have been updated to use surface fluxes from HRRR, adjusted for sub-grid topography. Incoming solar radiation is decomposed into its direct and diffuse components before applying the topographic corrections, and the simulated net solar radiation now uses the daily fractional snow albedo from MODIS retrieved via the spectral-unmixing algorithm SPIReS. Incoming longwave is adjusted for topography and accounts for thermal emission from surrounding terrain. Together, these new radiative forcing inputs in iSnobal decrease the simulated net radiative balance by 7 Wm-2 (averaged over the 2022 water year across a snow-dominated watershed in the headwaters of the Colorado River). These changes delay snowmelt, reducing melt-out date bias from 24–34 to 4–15 days early, depending on site and year. Lidar-based snow depth assessment shows a reduced mean bias −37cm to −15cm near peak SWE and from −18cm to −11cm later in the 2022 melt period. Together, these updates improve the ability of iSnobal to capture radiative heterogeneity in complex terrain, and enhance snowmelt predictions for mountain watersheds in operational modeling frameworks.

Authors: *Guillermo Rodríguez-López, Ignacio Cazcarro, Miguel Ángel Almazán-Gómez, Juan Ignacio López-Moreno, Jesús Revuelto*

No Snow, No Flow: Tracing Snowmelt Shortages Through Agricultural and Hydropower Chains

Water availability is a critical challenge for Mediterranean regions, where climate change exacerbates the frequency and severity of droughts. These regions heavily depend on snowmelt from mountain basins, which acts as a natural reservoir that supplies water during peak summer demand. This study examines how disruptions in snowmelt water availability affect agricultural production and their cascading economic impacts across sectors and regions, using an innovative hydro-economic model integrated with a multiregional input-output (MRIO) framework.

The hydro-economic model provides a detailed analysis of the Ebro River Basin, divided into 17 zones to capture intra-annual water dynamics. It incorporates key processes, including inflows, outflows, reservoir management, and water allocation across agricultural, industrial, and domestic sectors. A novel aspect of this model is the explicit consideration of snowmelt as a distinct water source, allowing precise quantification of its contribution to agricultural productivity and hydropower production. The integration of data from the SWAT model enables simulations of snowmelt reduction scenarios aligned with climate projections, emphasizing the vulnerability of regions dependent on nivopluvial regimes.

The MRIO model complements this hydrological analysis by linking agricultural outputs to broader economic systems. It includes 428 sectors, covering the Ebro Basin, Spain, the EU, and global markets. This framework allows the tracing of intersectoral dependencies and reveals how localized water shocks propagate through supply chains, creating ripple effects that impact both regional and international economies. The inclusion of interconnected sectors like food processing, logistics, and trade highlights the broader economic risks posed by declining water availability.

Preliminary results highlight the Ebro Basin's significant reliance on snowmelt water, with projected snowpack declines leading to the loss of close to 7 thousand equivalent jobs and more than €200 million in value added, mostly (~92%) of which is concentrated in the Spanish economy. The reduction in water availability impacts not only farming but also downstream industries essential to regional economies. These findings underscore the need for adaptive water management strategies to mitigate economic losses and maintain resilience.

Simulations demonstrate how changes in snowmelt availability disrupt water allocation patterns, reduce agricultural yields, and weaken overall economic performance and quality of life. The study's integration of detailed hydrological and economic frameworks provides actionable insights for policymakers. It emphasizes the critical role of snowmelt in sustaining current economic activity, lifestyles and ensuring the stability of vulnerable communities and industries in the face of climate change. It also highlights the irrationality of increased water demands

Authors: *Guillermo Rodríguez-López, Juan Ignacio López-Moreno, Jesús Revuelto*

Snow Droughts in the Pyrenees (1959–2022): Trends, Structural Breaks, and emerging Asymmetries

This study examines the evolution of snow droughts in the Pyrenees from 1959 to 2022 using the Standardized Precipitation Index (SPI) applied to snow water equivalent (SWE) data derived from the S2M reanalysis (Vernay et al., 2021). SWE series were analysed by massif and elevation bands, allowing for a consistent assessment across the mountain range. The analysis combines descriptive statistics on frequency and severity of snow droughts, detection of structural breaks through the Bai-Perron test, and long-term trend estimation.

Our results reveal a significant intensification of snow droughts over the past decades, with two major turning points: the early 1980s and the late 2000s, when most structural breaks concentrate. These moments mark substantial reorganizations in snow regimes, indicating shifts in both the frequency and persistence of drought events.

Spatially, the findings highlight an increasing asymmetry between the southern and northern slopes of the Pyrenees. Since the mid-2000s, the southern side—particularly the central high-altitude areas—has experienced a sharp increase in both frequency and severity of snow droughts, while the northern side shows stabilization and, in some regions, even partial recovery.

The temporal analysis by subperiods suggests a progressive transition: snow droughts were relatively localized and less frequent before 1980; between 1980 and 2005, their occurrence expanded, especially in western and mid-altitude areas; and after 2005, an intensification on the southern slope contrasted with more stable or slightly improving conditions on the northern side.

Trend analysis confirms this divergence: most southern areas show negative trends in the snow-SPI, reflecting increasing snow scarcity, whereas parts of the northern slope exhibit neutral or even positive tendencies in the most recent decades.

Altogether, the results point to a reconfiguration of the Pyrenean snow system towards increasingly contrasted scenarios, with growing vulnerability on the southern slope and differentiated dynamics across the range. These findings have critical implications for water resource management, ecosystem services, and climate change adaptation strategies in mountain regions

Authors: *Maximiliano Rodriguez, Alvaro Ayala, Michael McCarthy, Catriona Fyffe, Thomas Shaw, Achille Jouberton, Emanuele Romano, Simone Fatichi and Francesca Pellicciotti*

Snow evolution during past droughts in the Central Apennines

As a result of climate change, mountain regions in South Europe are experiencing changes in temperature and precipitation patterns. Periods of low precipitation can reduce winter snow accumulation, while anomalous hot periods during spring and summer can accelerate snowmelt, altering the water cycle and discharge patterns of mountain systems and their downstream areas. Warmer and drier conditions increase water scarcity, disrupt water supplies, reduce crop yields and decrease hydropower generation through increased evapotranspiration and reductions in streamflow and groundwater recharge. In this study, we investigate the main effects of droughts on the hydrosphere, biosphere and pedosphere in the Tiber basin, in the Apennine mountains of Italy, using the land surface model Tethys-Chloris from 2000 to 2010. Our model configuration resolves energy budgets and mass balances at an hourly step and 250m resolution to simulate processes such as snowmelt, sublimation, plant transpiration, infiltration, among others. We force the model using a combination of station and reanalysis data to evaluate it against streamflow measurements and remote sensing products including snow cover area and leaf area index. We analyze distributed high-resolution maps of modelled snow depth, snow water equivalent, infiltration, soil moisture, lateral subsurface water fluxes and surface temperature to obtain a highly resolved picture of the functioning of the mountain system in the central Apennines and its compounded changes during the droughts of 2003 and 2007. This allows us to identify changes produced by droughts on snow accumulation and the seasonality and magnitude of runoff, as well as shifts in altitudinal patterns in snowmelt and evapotranspiration. We investigate the response of specific types of vegetation at different elevations produced by lower snow accumulation rates and a higher snow line. Our findings indicate that periods of reduced snow accumulation lead to increased high-elevation evapotranspiration, likely driven by the early greening of vegetation. The implementation of the model in the Central Apennines provides a new tool with unprecedented physical, spatial and temporal details to understand the consequences of droughts on the mountain water cycle, taking into account both vegetation and snow effects on streamflow generation.

Authors: *Francisco Rojas-Heredia, Jesús Revuelto, Esteban Alonso- González, Cesar Deschamps-Berger, Javier Bandrés, Pablo Domínguez, Eñaut Izagirre & Juan Ignacio López-Moreno*

Integrating UAV-derived snow metrics with thermal monitoring of soil, air and vegetation in a marginal snowpack environment of the Pyrenees

Marginal snowpack is relatively new concept, referring to snow conditions that are typically shallow, patchy, and characterized by recurrent accumulation–ablation cycles within the snow season. Its variability makes snow distribution highly sensitive to local-scale processes, where interactions among vegetation, microtopography, and snowpack dynamics strongly influence snow evolution.

This research applies an integrated approach that combines high-resolution spatial and micro-meteorological monitoring to investigate shrub and microtopographic controls on snow distribution. The study was conducted near the Cotefablo mountain pass (1700 m a.s.l., central Pyrenees), a transitional zone between treeline forest and subalpine shrubland dominated by *Buxus sempervirens*, *Echinospartum horridum*, and *Juniperus communis*.

Since December 2021, 21 TMS dataloggers have continuously measured air and soil temperature and soil moisture at multiple heights, depths and microsites (within shrubs, at trunks, into soil and in adjacent open areas). In parallel, 24 UAV surveys equipped with LiDAR or RGB sensors have produced 3D point clouds from which ultra–high-resolution (0.2 m) raster layers were derived. These data have enabled to determine, snow depth (SD), snow presence (SP) spatial distribution, and to derive distinct vegetation–topographic metrics. Combined with local meteorological records, these detailed datasets allow us to examine vegetation- and soil-driven thermal effects and their role in snow–vegetation–microtopography energy and mass feedbacks.

Preliminary results indicate that shrub patches exert a dominant influence on snow spatiotemporal distribution. Vegetation height and local topography modulate wind-blowing snow redistribution, while snow cover provides variable thermal insulation to soils depending on shrub type and location. The local thermal regime influenced by shrub presence affects differently snowpack accumulation and melting patters, while multi-year monitoring highlights strong interannual variability in marginal snowpack persistence, with no consistent trend across seasons.

This work advances understanding of snow–vegetation-microtopography interactions in Mediterranean mountain environments and provides transferable methodologies for monitoring marginal snowpacks. The results have direct implications for predicting hydrological responses to climate change in seasonally snow-covered shrublands and for improving water resource management in mountain regions.

Authors: *Freddy Saavedra, Ana Hernández-Duarte, Alex Caro, Antoine Rabatel, Steven Fassnacht, Thomas Condom, Stephanie Kampf, Mariano Masiokas, Carlos Romero, Yael Aguirre, Daniela González, Valentina Contreras, Javier Medina and Pablo Arancibia*

Spatial and Temporal Variability of Snow in the Andes using MODIS Snow Product 2000-2024

Snow is a vital component of the Andean hydrological system, particularly in central and southern regions, where snowmelt supports agriculture, hydropower, urban water supply, and industry. However, ongoing climate change is reshaping temperature and precipitation patterns, with significant impacts on snow cover dynamics. The Andes span a wide latitudinal range (10°N to 57°S), encompassing diverse climatic and topographic zones. Monitoring snow cover across this range is challenging due to persistent cloud cover. In this study, cloud reduction algorithms reduced cloud persistence (CP) from 49% to 29%, enhancing the reliability of snow observations across the region. This study presents a comprehensive analysis of the spatial and temporal dynamics of snow cover across the Andes Mountains from 2000 to 2024, using satellite-based data from the Moderate Resolution Imaging Spectroradiometer (MODIS) combined with advanced cloud reduction algorithms. The results show a marked decline in snow persistence (SP) between 29°S and 36°S, with an estimated loss of approximately 78,000 km² of snow-covered area over 24 years. The snowline has risen by up to 500 meters in this region, with annual increases of 5–15 meters, mainly driven by temperature increases and the upward shift of the 0°C isotherm. In contrast, southern Andes regions display more stable snow patterns, although localized increases in SP may reflect changes in cloud detection rather than actual snow dynamics. Watershed-scale analysis highlights spatial heterogeneity. Tropical basins exhibit minimal snow cover confined to high elevations, while central Andes basins (29-36°S) show significant SP declines and snowline elevation increases. Southern basins generally maintain stable snow conditions, though cloud cover remains a limiting factor for full assessment. The continued reduction of SP, particularly in the central Andes, presents serious challenges for water management in regions where snowmelt is critical for sustaining water supply. This study underscores the need to advance snow monitoring through higher-resolution remote sensing, expanded ground-based observations, and integration of snow water equivalent (SWE) data. Such efforts are essential for improving water resource management and enhancing climate resilience throughout the Andes.

Authors: *Alejandro Sánchez Reina, Jesús Revuelto, Antonio Sarsa, Sol Carretero Palacios and Alberto Jiménez Solano*

SnowDISOR: A Monte Carlo Model for Light Propagation in snowpack layers with micro- and nano-particle inclusions

Alejandro Sánchez Reina,[1] Jesús Revuelto,[2] A. Sarsa,[1] Sol Carretero Palacios,[3] and Alberto Jiménez Solano[1]

[1]Departamento de Física, Universidad de Córdoba, Edificio Einstein, Campus de Rabanales, Córdoba, Spain

[2]Pyrenean Institute of Ecology, Spanish National Research Council, Zaragoza, Spain

[3]Instituto de Ciencia de Materiales de Madrid, ICMM-CSIC, C/Sor Juana Inés de la Cruz, Madrid, Spain

We present a Monte Carlo-based numerical model for simulating light propagation in snowpack layers, incorporating the key physics of both scattering and absorption in optically disordered media. **SnowDISOR** is an adaptation of an optical ray tracing model originally developed for disordered nanostructured materials, such as dye-sensitized solar cells and nanoporous matrices, and has been extended to account for larger particles like snow grains. It combines Fresnel-based geometric optics with Mie scattering theory to simulate photon interactions with complex media containing both micro- and nano-scale structures, including nano-particles such as microplastics, soot, and dust embedded in snow and ice.

SnowDISOR allows for the construction of multilayer snowpacks, where each layer can be independently configured in terms of snow grain size, impurity size and concentration, density, and specific surface area (SSA). This flexibility enables the simulation of realistic stratified snow systems with spatially heterogeneous micro- and nano-structures, addressing key limitations of existing deterministic models.

The inclusion of nano-particles is handled through Mie theory, allowing accurate treatment of both scattering and absorption by particles comparable in size to solar wavelengths. This is essential for studying the optical impact of atmospheric impurities, which can significantly influence the snow albedo and, consequently, energy balance and melt rates.

SnowDISOR successfully reproduces measured spectral albedo curves for fresh snow at Summit, Greenland, in the 400–2500 nm range, without the need for empirical tuning. By matching simulated and observed optical responses, the model also enables the extraction of internal snowpack parameters such as mean grain size and impurity content, offering potential applications in remote sensing and inverse modeling. Preliminar tests with spectral albedo observations in the 400-950 nm range retrieved in the Pyrenees, show reliable results with different surface snow conditions.

Overall, SnowDISOR provides a versatile framework for exploring the influence of snow micro- and nano-structure and embedded impurities on radiative transfer. Its physically grounded design makes it a useful

tool for advancing the study of snow optics, with possible implications for climate modeling, satellite data interpretation, and the investigation of impurity-related effects in cryospheric systems.

Authors: *Mel Sandells, Esteban Alonso-González, Richard Essery, Leena Leppänen, Nicolas Leroux, Franck Lespinas, Julien Meloche, Vincent Vionnet*

Assimilation of multichannel passive microwave data for improved estimates of snow microstructure

Snow is a vital water resource yet is difficult to monitor with satellites due to the sensitivity of the signal to both mass and microstructure at microwave frequencies. Inversion of forward radiative transfer models to obtain snow water equivalent requires a priori estimates of snow structure. On large scales, this is derived from land surface models. Although these models may capture important structural evolution processes such as melt and snow crystal metamorphism, the size and shape of snow crystals may not be represented with sufficient accuracy required for snow water equivalent retrieval. Penetration of the microwave radiation depends on the frequency, with higher frequencies more sensitive to surface properties and lower frequencies responsive to properties lower in the snowpack. Assimilation of multifrequency remote sensing observations may help to constrain layered snow microstructure in the model. Here, we use the Multiple Snow Data Assimilation system to quantify the change in snowpack properties from assimilation of passive microwave data in the frequency range 1-36 GHz. A range of assimilation techniques and frequency combinations are presented. Implications for use of data from the planned Copernicus Imaging Microwave Radiometer mission are discussed.

Authors: *María Santolaria-Otín, Charles Amory, Martin Ménégoz, Xavier Faïn, Fanny Brun, Christopher Mayer and Astrid Lambrecht*

High-Resolution Reanalysis Insights into Climate Variability over High Mountain Asia

High-elevation regions with complex orography pose major challenges for estimating local precipitation and snow-related variables due to sparse observations and strong spatial variability. To bridge this gap, the Modèle Atmosphérique Régional (MAR) has been used to generate a high-resolution,long atmospheric reanalysis over High Mountain Asia spanning 1980 to the present. The model has been calibrated using both local meteorological observations and remote sensing, and is driven by ERA5 reanalysis (1950–present) to achieve a comprehensive coverage of the mid 20th century. This atmospheric reanalysis provides unprecedented insights into interannual variability, long-term trends, and the links between large-scale atmospheric circulation and local climatic conditions, including elevation contrasts. Its fine spatial resolution significantly serves to improve our understanding of cryosphere-climate interactions and supports a wide range of applications in High Mountain Asia.

Authors: *Cristóbal Sardá, María Courard, Gonzalo Cortés, James McPhee*

Assimilating hydrological variables with particle filters to improve distributed snow modeling and spatial precipitation patterns

Understanding snow accumulation and distribution in high mountain regions, as well as snow water equivalent (SWE), is crucial for accurate hydrological forecasting in snow-influenced catchments. A major challenge in these systems is the scarcity and complexity of snow-related observations, which necessitates the use of hydrological models capable of simulating snow processes at larger scales. However, both observations and models are subject to different sources of uncertainty, affecting prediction accuracy. Data assimilation techniques help improve predictions in such uncertain scenarios. Among these, particle filters (PF) are particularly suitable for nonlinear systems. This study aims to reduce uncertainty in key snowpack variable predictions in the Andes mountains by implementing PF and assimilating hydrological variables. Additionally, it explores the variability in spatial precipitation patterns by updating and correcting state variables through discretization into elevation bands. The study domain is El Yeso basin in Chile, and the hydrological model used is the Canadian Hydrological Model (CHM), a physically based distributed model that represents terrain using irregular triangular elements. Specifically, the work focuses on state variables such as SWE, input variables like solid precipitation, and the use of observations from remote sensing products such SCA/SCF. This approach constrains uncertainty, enabling updated predictions with reduced variability.

Authors: *Andrew Schwartz, Marianne Cowherd, Megan Mason, Mia Jones and Kiana Tsao*

Implementation of an Automated Height-Adjusted Arm for Snowpack Turbulent Flux Measurement

Accurate measurement of turbulent fluxes above the snowpack is vital to our understanding of its energy balance and interactions with vegetation and topography. Additionally, consistent measurement of snowpack turbulent fluxes is crucial for the calibration and validation of snowpack models used for forecasting water resources. However, most turbulent flux measurement systems assume static surface height, leading to significant challenges when taking observations over a dynamic snow surface. To address these challenges, the Central Sierra Snow Laboratory (CSSL) has developed and implemented a moving arm assembly that allows for constant-height measurement of turbulent fluxes with a Campbell Scientific IRGASON system. This has enabled reliable snowpack turbulent flux measurements at the CSSL in the face of unique climatic challenges, including averaging 9 meters of snowfall annually (exceeding 18 meters in large years) and regular mid-season ablation periods. This presentation will highlight the moving arm system and its preliminary performance during water year 2025.

Authors: *Aynur ?ensoy, Mevlüthan Sakall?, Aynur ?ensoy, Arda ?orman, Francesco Avanzi, Simone Gabellani*

Evaluating Snow Dynamics with Multiple Forcing and Assimilation Strategies for a Mediterranean Catchment in Türkiye

Snow, as a fundamental component of the cryosphere, constitutes one of the most important interfaces on Earth. It acts not only as a major source and reservoir of freshwater in certain regions but also as a key regulator of the Earth's energy balance through its high albedo, thereby contributing to the stabilization of surface temperatures. However, climate change is profoundly altering global snow dynamics, leading to increased uncertainty in snow forecasts and, consequently, jeopardizing the stability of water resources in snow-dependent areas. This challenge is particularly evident in the snow-dominated headwaters of a Mediterranean Basin, Seyhan Basin, one of Türkiye's largest river basins, which encompasses one of the country's most fertile plains and sustains significant dam operations and hydropower production. The basin exhibits a pronounced climatic gradient: lower elevations are characterized by the temperate and humid Mediterranean climate, whereas the upper mountainous regions possess substantial snow storage potential. Its complex topography and mixed climatic influences render the Seyhan Basin a challenging yet ideal natural laboratory for investigating the snow resources and hydrological processes.

This study aims to advance the understanding and spatial characterization of snow processes in this complex Mediterranean basin through comprehensive snow modeling and assimilation using multi-source data approach. The performance of the physically based, distributed Snow Multi-Data Mapping and Modeling (S3M) framework was rigorously evaluated for multiple snow components. Three distinct S3M model configurations were developed using (i) in-situ meteorological observations, (ii) ERA5-Land reanalysis data, and (iii) MSWX-Historical reanalysis data as forcing. The relatively low data requirements of S3M confer a considerable advantage for data-scarce regions. All model setups span 2014–2024 water years. Furthermore, to enhance model performance, a snow data assimilation framework employing the C-Snow (Sentinel-1) snow depth product was implemented for 2020–2023. Snow depth simulations were validated against ground-based observations, while snow-covered area (SCA) and snow-water equivalent (SWE) estimates were assessed using independent satellite (MODIS-CGF, IMS-4km, SE-D-SEVIRI, SWE-E) and reanalysis products (ERA5-Land). Pixel-based model evaluations were conducted using a contingency-table approach and a suite of performance metrics. Probability of Detection (POD) for SCA was calculated as high as 0.86 for the observation-driven, 0.84 for the ERA5-Land-driven, and 0.73 for the MSWX-Historical configuration. Corresponding False Alarm Rate (FAR) values were 0.18, 0.22 and 0.13 respectively.

This integrated modeling and assimilation framework provides a robust and spatially explicit representation of snow resources under changing climatic conditions, offering critical insights for sustainable water management in complex Mediterranean basins.

Authors: *Ian Shirley, Chen Wang, Zelalem Mekonnen, William J. Riley, Baptiste Dafflon*

Extracting Site-Specific Controls on Snow-Permafrost Interactions from Distributed Temperature Profiles Using Data-Model Integration

Snow-permafrost interactions play a central role in cold-region hydrology and permafrost stability. In discontinuous permafrost landscapes, maximum snow depth is often used as a predictor of permafrost vulnerability, yet this simple metric obscures the complexity revealed by high-resolution observations. Snow and soil temperatures vary sharply across short distances, shaped not only by snow depth but also by soil thermal properties, hydrologic state, and evolving snowpack characteristics such as densification and thermal conductivity. These interacting factors complicate efforts to isolate the drivers of observed dynamics, even with dense observational networks. Process-rich ecosystem models such as *ecosys* provide a way to probe these controls, but their high computational cost constrains traditional sensitivity analyses and parameter estimation.

We address this challenge with a framework that integrates distributed temperature measurements with a machine-learning surrogate of *ecosys* to extract site-specific controls on snow-soil heat transfer. The approach is applied to a Distributed Temperature Profiling (DTP) network spanning more than 100 sites across two watersheds on the Seward Peninsula, Alaska. Over two years, the network recorded continuous time series profiles of snow depth, snowpack temperatures, and soil temperatures with high vertical resolution. A convolutional neural network surrogate, trained on *ecosys* simulations, provides the computational efficiency needed for Bayesian Markov Chain Monte Carlo estimation of parameters governing soil thermal and hydrologic properties, microclimate gradients, and snow conductivity.

Results show that temperature time series contain strong diagnostic information about subsurface and snowpack properties. Posterior estimates substantially improve model skill in reproducing snowpack evolution and soil thermal responses, while quantifying uncertainty and identifying interactions among snow, soil, and water processes that govern heat transfer. By combining machine-learning acceleration with a process-rich ecosystem model, this framework transforms dense time series into quantitative constraints on hard-to-measure properties, advancing predictive understanding of snow-permafrost dynamics under Arctic change.

Authors: *McKenzie Skiles, Chris Donahue, Janice Brahney*

Are microplastics melting snow? An optical property and radiative forcing assessment in the Western US

Snow sample analysis from a range of environments, from midlatitude mountains to the arctic, document that microplastic deposition is widespread across the cryosphere. Previous work has noted the presence of microplastics, quantified particle size and types, and compared microplastics through time and across snow environments. However, there has been relatively little work done to assess if microplastics are darkening snow cover. This is challenging due to the diversity of microplastic particle origin, color, and size/shape. We make a first order assessment of the radiative forcing potential of microplastics using available reflectance measurements of microplastics and tire rubber and forward modeling. The retrieved microplastic optical properties were built into a snow and aerosol radiative transfer model to simulate snow spectral reflectance with and without microplastics. The spectral reflectance pairs were then used to quantify the snow darkening (perturbation to snow albedo), radiative forcing (additional absorption of solar radiation), and melt contribution. The microplastic concentrations in the model were based on volumetric polymer deposition rates, partitioned by color over a three successive snow-covered periods in the Rocky Mountains of Colorado, USA. For context, the impacts of microplastic in snow will be compared to radiative forcing by other common aerosols, including mineral dust and black carbon. In addition, we consider the broader implications by estimating volumetric deposition using published microplastic concentrations in snow samples around the world.

Authors: *Ayca EYLEN, Arda SORMAN, Aynur SENSOY*

Multi-criteria hydrologic modeling using MODIS snow cover and SMAP soil moisture satellite products

Hydrological models are typically calibrated using long-term and continuous in-situ streamflow observations. However, single-objective calibration approach that focus solely on streamflow do not always yield reliable or realistic predictions. This is because different parameter sets may produce similar streamflow simulations while leading to significant discrepancies in other hydrological components. To address this issue, multivariate calibration strategies that incorporate additional hydrological variables such as snow cover and soil moisture can help reduce the problem of equifinality and enable more consistent and accurate simulations. In this study, the role of remote sensing data in hydrological model calibration was investigated using the HBV-type TUWmodel in two mountainous catchments in Türkiye. The model was calibrated under different scenarios using not only streamflow data but also cloud-free MODIS snow cover and SMAP root zone soil moisture products. The inclusion of soil moisture and snow cover data enhances the simulation of their respective components: soil moisture and snow processes. When both data sources are combined, improvements are observed in both areas. Additionally, snow-related parameters are influenced by snow data, while soil parameters are affected by soil moisture data. These findings highlight the importance of integrating multiple remote sensing products into hydrological model calibration to achieve a more realistic representation of hydrological processes. The results also underscore the value of satellite observations, particularly in data-scarce catchments where in-situ measurements are limited or unavailable.

Authors: *Laur Sourp, Simon Gascoin, Lionel Jarlan, Vanessa Pedinotti, Lahoucine Hanich*

Snow droughts around the Mediterranean during the 2000-2024 period

The Mediterranean region is often regarded as a hot spot for climate change, especially in the matter of hydrological droughts. In this region, the cold season coincides with the wet season so snow storage is particularly important for water resources. We selected several catchments under a snowmelt hydrological regime around the Mediterranean : two in the Pyrenees (France), two in the Atlas (Morocco) and three in Mount Lebanon (Lebanon). We used ERA5 data as meteorological forcings for a snowpack model called SnowModel, where we perturbed the precipitation and temperature. Then, we used a data assimilation filter called the Particle Batch Smoother with MODIS snow cover fractions observations to produce a SWE reanalysis at 100 m resolution for the 2000-2024 period. We computed the Standardized SWE Index (SWEI) for the January-February-March season and compared dry events over the three mountain ranges. We observed that snow droughts are not happening simultaneously in the three mountain ranges. However, most snow droughts events are attributed to simultaneous "hot and dry" snow seasons, only one event in each mountain range is attributed to a "dry" snow season and two events in Mount Lebanon are attributed to a "hot" snow season. These two hot snow season events illustrate the vulnerability of Mount Lebanon to the increase in temperature as a large part of the snow storage is located on a plateau of relatively low elevation (around 2000 m a.s.l.). During this relatively short time period, we do not observe significant trends of snow droughts occurrence across these catchments, nor trends in the peak SWE accumulation. There is however a decreasing trend for the January SWE accumulation in the Atlas.

Authors: *Eric A. Sproles, Duilio Fonseca-Gallardo, Shannon Hamp, Joe Shaw, Erich Schreier, Henna Hannula-Retta, Roberta Pirizzini, Riley Logan*

UAV-based hyperspectral imaging to evaluate uncertainties in multispectral remote sensing and modeled snow reflectance

We present an evaluation of Level-2 surface reflectance products from Landsat 8 and 9 using measurements from UAV-based hyperspectral imaging across three different snow types – alpine, prairie, and taiga in Montana (USA), Montana, and Finland; respectively. Using two commercial hyperspectral sensors (Resonon Pika L and IR-L), we captured surface reflectance across the VIS–NIR–SWIR range (400-1700 nm; Landsat Bands 1-6) at high spectral (>250 bands) and spatial (0.3 m) resolution. We applied a convolutional neural network (CNN) for supervised classification to identify snow-only pixels for assessment. Our results highlight systematic discrepancies in Landsat reflectance. Notably, there were strong overestimations in Bands 1, 2, and 5, and a consistent underestimation in Band 6 (SWIR1), with surface reflectance biases reaching up to 17%. The CNN-based classification revealed considerable spatial variability in snow reflectance, emphasizing the shortcomings of assuming uniform surface conditions across snowy landscapes. We also present the design and calibration of a custom UAV-based radiometer system for validating snow surface reflectance measurements from Landsat Band 7 (SWIR2) and Sentinel-2 Band 12. The radiometer was constructed using single-pixel photodiodes and custom bandpass filters to match the spectral range of Landsat Band 7 (1210-2290 nm). It was fully calibrated across a range of various temperatures in a controlled laboratory. When flown at 120 m, the radiometer has a ground swath diameter of 14.39 m, providing a spatial resolution over four times greater than the 30 m resolution of a Landsat Band 7 pixel. Over alpine snowpack, the calibrated Band 7 system surface reflectance measurements ranged between +46.9% and -27.0% with respect to the Landsat Band 7 reflectance measurements.

Accurate surface reflectance estimates over snow-covered landscapes are critical for the development of reliable satellite-based albedo products. These combined results highlight the limitations of relying on satellite-derived surface reflectance measurements across snow-covered landscapes. However, robust validation data in such environments remain scarce, especially at high spatial resolution. Combined, our methods and findings highlight the need to enhance validation strategies for snow-covered regions and provide a scalable protocol that integrates UAV-based acquisitions, high-resolution spectral measurements, and supervised scene analysis.

Authors: *Leonardo Stucchi, Maurizio Maugeri, Veronica Manara, Diego Jacopino, Daniele Bocchiola*

Hydro-meteorological regime of Alpine catchments under recent climate change. A case study from Northern Italy and Southern Switzerland.

This study investigates the impact of climate change upon the hydro-meteorological regime of 5 Alpine catchments, spanning North-West Italy and South Switzerland, all tributaries of Po River, the main river of Italy. Changes in climatic variables, i.e. measured precipitation, temperature, and potential evapotranspiration, were derived from 25 weather stations, spanning from 1979-2022, were examined alongside streamflow data from 15 river sections to detect significant trends and correlations. Trends were assessed both using Theil-Sen regression, robust to assess linear trends in presence of outliers, and Mann-Kendall test, reliable for detecting monotonic trends, including those that are non-linear. Our results show a most pronounced trend in maximum daily air temperature (+0.60 °C/10y), especially during spring (+0.95 °C/10y). and lower for average and minimum daily values (+0.50 °C/10y and +0.39 °C/10y respectively). Consequently, potential evapotranspiration shows consistent increase (+15.1 mm/10y), along with a relevant decline in summer streamflow in 10 out of the 15 sections considered, while a weak increase in winter streamflow is expected due to lower snowfall accumulation. Strong correlations were found between streamflow and both precipitation and summer temperature. By focusing on an understudied portion of the Alps, this work contributes novel insights into the hydrological impacts of climate change within the Po River basin, a crucial area for industrial and agricultural production of Europe.

Authors: *Adrián Subías Martín, Víctor Herráiz-López, Iñigo Salinas, Samuel T. Buisán and Rafael Alonso*

From Physical Modeling to Electromagnetic Simulation: Understanding Snowpack Stratigraphy Using an SFCW Radar

Understanding the internal structure of the seasonal snowpack is essential for hydrological modeling, climate research and avalanche forecasting. Ground-based radars have demonstrated their ability to detect stratigraphic features. In this work, we present an integrated approach that combines a physically based snowpack evolution model with a multilayer electromagnetic simulation to interpret how a Stepped-Frequency Continuous-Wave (SFCW) radar can resolve the real stratigraphy of a snowpack.

In addition to its theoretical scope, this work highlights the potential of this type of radar for investigating the temporal evolution and stratigraphy of the seasonal snowpack. The simulations provide a framework to better interpret snowpack processes and directly support the experimental deployment of an operational SFCW radar system at the AEMET-Sarrios-Formigal test site.

The physical evolution of the snowpack is simulated using SNOWPACK, a widely validated multilayer model, driven by meteorological data from the Spanish State Meteorological Agency (AEMET), collected at the test site during the 2023-2024 season. The model provides the temporal evolution of the physical properties of each layer. The density and liquid water content (LWC) of each layer constitute the physical basis for the electromagnetic characterization of the snowpack.

The electromagnetic model, implemented as a plane-wave multilayer simulation, reproduces the behavior of an SFCW radar operating in the 0.6–6 GHz frequency range. Each layer is represented as a homogeneous, plane-parallel slab characterized by its complex refractive index and thickness. The multilayer structure is then processed with the plane-wave algorithm to simulate the radar reflection response.

The combined use of these simulations makes it possible to analyse how radar signals interact with complex and realistic snow profiles, capturing multiple reflections, attenuation and phase shifts caused by variations in density and LWC. The results show that the radar is capable of resolving layers only a few centimeters thick (due to the wide operational bandwidth), as well as detecting the presence and distribution of liquid water within the snowpack (highly reflective layers).

This study demonstrates the potential of radar for in situ monitoring of hydrological parameters, particularly for tracking and understanding the stratigraphic evolution of the snowpack. Furthermore, this framework enables controlled experiments on how specific processes (melting, refreezing or percolation) affect radar observations, opening new possibilities for the interpretation and operational use of radar measurements.

Authors: *Kazuyoshi Suzuki, Milija Zupanski, Steven R. Fassnacht, Yuki Sekiya, Takashi Dan, Hotaek Park, Hideki Kobayashi, Olga Makarieva, Tetsuya Hiyama*

Advancing the JAMSTEC Arctic Regional Reanalysis (JAMSTARs): A Nested Data Assimilation Approach for Improved Mountain Snowpack Representation

The JAMSTEC Arctic Regional Reanalysis system (JAMSTARs) is a regional reanalysis framework based on ensemble simulations that cover areas from the Arctic to the mid-latitudes. It routinely assimilates observational data from the US National Centers for Environmental Prediction (NCEP) PREPBUFR and provides tools to evaluate the impact of advanced land surface model parameterizations and satellite retrievals on reanalysis accuracy.

In this study, we present a newly developed nested data assimilation version of JAMSTARs designed to better capture fine-scale surface and cryospheric processes. The new system employs a parent domain with 27 km spatial resolution that covers the entire Northern Hemisphere, and introduces nested domains with 9 km resolution over key regions such as Alaska and Far-Eastern Siberia. These nested domains explicitly resolve complex topography and enable more accurate simulation of orographic precipitation and mountain snowpack. Sensitivity experiments demonstrate that nested data assimilation significantly improves the representation of snow depth and snow water equivalent in mountainous areas when compared with independent observations and ERA5.

This nested JAMSTARs framework will contribute to improved understanding of Arctic and sub-Arctic extreme weather, permafrost change, and hydrological processes. It also provides a powerful tool to evaluate the impact of various observational datasets and land surface schemes at scales relevant for high-resolution climate services and operational applications such as Arctic shipping route forecasting and regional water resource management.

Authors: *Mohsin Tariq, Francesco Avanzi, Luca Ciabatta, Mauro Rossi, Marco Donnini, Angelica Tarpanelli, Manuela Girotto, Christian Massari*

Integrated Satellite-Based Monitoring of Snow Cover Variability in the Mediterranean Region

Snow cover is a significant water resource component in the Mediterranean region. It acts as a natural reservoir, helping to regulate seasonal runoff and supporting mountain-fed river systems. The topographically complex and climatically diverse terrain, combined with sparse in situ observations and high spatial variability, makes it challenging to assess its dynamics.

In this study, we investigated long-term snow cover behavior over the Mediterranean region and four basins in this region, i.e., Po, Tiber, Crati, and Ebro. We used three satellite datasets: the Advanced Very High Resolution Radiometer (AVHRR), the Moderate Resolution Imaging Spectroradiometer (MODIS), and Sentinel-1 (S-1). By systematically comparing Snow Cover Ground Fraction (SCGF) from these sensors, we characterized spatial patterns, temporal trends, and responses to extreme events across the region.

Annual SCGF reveal distinct elevation-dependent gradients, with continual snow accumulation in high mountains and limited availability along coastal and lowland zones. Due to finer resolution, MODIS captures finer spatial variability than AVHRR; however, cross-sensor comparisons indicate decent agreement. S-1 snow depth converted to SCFG further validated the optical-based snow detection.

Extreme event-based anomaly assessment shows coherent snow cover responses during extreme drought years, particularly 2005 and 2022. Widespread negative anomalies over the Mediterranean region mark the 2022 drought. Basin-scale performance assessments when AVHRR compare with S-1 show that high-elevation areas such as the Po basin exhibit the strongest inter-sensor agreement. In contrast, smaller and more heterogeneous basins like the Tiber and Crati represent more variability.

The SCFG trend analyzed based on AVHRR data indicates statistically significant declines in regional snow cover over recent decades, though basin-specific trends are controlled by strong interannual variability. The findings broadly demonstrate the importance of multi-sensor satellite integration for monitoring snow cover dynamics in the climatically sensitive Mediterranean domain, highlighting pronounced spatial heterogeneity in snow-climate interactions.

Keywords: Snow cover, Mediterranean climate, AVHRR, MODIS, Sentinel-1, Climate change

Authors: *Jack Tarricone, Ross T. Palomaki, Zach Hoppinen, Randall Bonnell, Shadi Oveisgharan, Jorge Jorge Ruiz, Hans-Peter Marshall, Elias J. Deeb, Carrie Vuyovich, Richar R. Forster, Steven A. Margulis, Simon Yueh, Ryan W. Webb, Dan McGrath, Juha Lemmetyinen, Kelly Elder, Rashmi Shah, Xiaolan Xu, Mario Chaubell, Micah Johnson, Micah Sandusky, Mark Robertson, Thomas Painter, and Curtis Beutler*

Towards InSAR-Based Seasonal Snow Monitoring: Preparing for NISAR and the Road Ahead to ROSE-L

In recent years, Interferometric Synthetic Aperture Radar (InSAR) has shown great potential for monitoring snow water equivalent (SWE) and snow depth under certain conditions. Such data are crucial for water resource management, flood forecasting, agricultural planning, and transportation and avalanche safety. Key advancements have been driven by the NASA SnowEx Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) campaigns and European Space Agency (ESA)–funded airborne and satellite research. This progress provides critical preparation for the recent launch of the NASA–ISRO SAR (NISAR) and the forthcoming Copernicus Radar Observing System for Europe at L-band (ROSE-L) mission, anticipated near the end of the decade. However, several key uncertainties in InSAR's snow monitoring capabilities must be addressed before the technique can be implemented operationally and systematically. These include challenges related to reference phase calibration, complex mountain topography, atmospheric phase delay, forest cover, and snow wetness. Here, we synthesize recent advances to assess the technique's current capabilities and outline ongoing work toward the first winter of NISAR-based retrievals in 2026. We conclude with recommendations on structuring field validation efforts, advancing open-source software, and integrating InSAR with complementary remote sensing and modeling frameworks to fully leverage NISAR and ROSE-L. While InSAR will not be universally applicable, it is poised to become a vital component of future global snow monitoring.

Authors: *Sara Tegoni, Riccardo Barella, Carlo Marin, Umberto Morra di Cella, Biagio di Mauro, Jesús Revuelto*

Evaluating Snow Cover Fraction Retrieval Across Methods and Multispectral Sensors

Snow Cover Fraction (SCF) indicates the snow-covered percentage of an area and is a crucial variable for monitoring snow dynamics and supporting hydrological modeling. SCF can be derived from multispectral optical satellite imagery by exploiting the rich spectral information. This study evaluates and compares the performance of state-of-the-art SCF retrieval methods across multiple satellite sensors with varying spatial resolutions. Four satellite sensors are considered in the analysis: Sentinel-2 (20m), Sentinel-3 OLCI (300m), MODIS (500m), and VIIRS (375m). The SCF methods tested consist of NDSI-based and multispectral unmixing approaches. In detail, two NDSI-based regression methods are tested: linear [1] and sigmoid [2] relations between SCF and NDSI. Since Sentinel-3 OLCI lacks SWIR bands, a dedicated snow index and regression coefficients are tested. NDSI is also used to create a binary snow map, by applying a threshold. Moreover, linear [3] and non-linear [4] multispectral unmixing is performed, with local endmember selection. A control method, based on a pseudo random SCF based on the NDSI is also considered. To investigate capabilities under different environmental and spatial conditions, different dates and regions of interest are considered, using Very High Resolution (VHR) imagery to create highly precise SCF reference maps for evaluation. SCF maps from different methods and sensors are evaluated using fractional metrics (RMSE, MBE), along with Snow Cover Area (SCA) estimation. Metrics are computed across SCF classes, and spatial error distribution is analyzed to explore links between retrieval capabilities and topography. Comparing performances of methods and sensors contributes not only to understanding the strengths and weaknesses of each combination, but also to comprehending the limits of SCF estimation, especially in relation to the complexity of the terrain.

[1] Salomonson, Vincent V., and I. Appel. "Estimating fractional snow cover from MODIS using the normalized difference snow index." Remote sensing of environment 89.3 (2004): 351-360.

[2] Gascoin, Simon, et al. "Estimating fractional snow cover in open terrain from sentinel-2 using the normalized difference snow index." Remote Sensing 12.18 (2020): 2904.

[3] Keshava, Nirmal, and John F. Mustard. "Spectral unmixing." IEEE signal processing magazine 19.1 (2002): 44-57.

[4] Barella, Riccardo, et al. "A novel approach to high resolution snow cover fraction retrieval in mountainous regions." IGARSS 2022-2022 IEEE International Geoscience and Remote Sensing Symposium. IEEE, 2022.

Authors: *Théo Rétif, Simon Gascoin, Laura Sourp, Emma Denise, Camille Rogeaux*

High-Resolution Snow Water Equivalent Modeling in Franco-Italian Alpine Parks: The ACLIMO Project

Climate change is disrupting water resource availability in alpine regions with consequences for high-altitude fauna, flora, and human activities. The ACLIMO project (Interreg-Alcotra) addresses critical water resource challenges in eight alpine parks across France (Vanoise, Écrins, Mercantour) and Italy (Gran Paradiso, Alpi Cozie, Alpi Marittime, Alpi Liguri, Gesso e Stura). The ACLIMO project combines climate adaptation awareness through communication and environmental education, climate impact assessment on water resources and ecosystems, and support for sustainable pastoral practices. The snow hydrology component of the project focuses on developing a high-resolution snow water equivalent (SWE) estimation pipeline to improve knowledge of water resources available from snowmelt. We developed an automated, generalizable snowpack modeling framework to produce spatially distributed snowpack simulations at 100 m resolution from 2015 to 2024 on the eight parks studied. The methodology is based on SnowModel, using the Copernicus ERA5 reanalysis data as meteorological forcing. Climate data downscaling to 100 m resolution employs the MicroMet module, using the Copernicus digital elevation model. The modeling chain simulates physical snowpack processes including mass and energy balances. Sentinel-2 snow cover observations from the Theia Snow collection are assimilated through a Particle Batch Smoother data assimilation method. This integration of high-resolution snow maps helps keep model consistency with satellite observations while accounting for meteorological uncertainties through ensemble simulations. We evaluated the simulations against ground-based measurements and MODIS satellite observations. The results demonstrated the good performance of the model across different elevation zones and snow conditions, with RMSE values typically below 30 cm against in situ snow depth measurements. Satellite data evaluation confirmed a strong agreement, with high correlation values, between simulated and observed snow-covered area dynamics. Therefore, our pipeline provides high-resolution spatially distributed SWE data including uncertainties that can be easily aggregated to watershed-scale to support water management in the parks.

Authors: *Laura Thomson and Sofia Guest*

A century of snow accumulation on Axel Heiberg Island, Canadian high-Arctic

The Arctic is warming at nearly four-times the global rate. Predictions of wetter conditions accompanying this warming have been substantiated by atmospheric observations, however there are limited *in situ* records available for validation in the high-Arctic. Field studies supporting glacier mass balance monitoring on Axel Heiberg Island, NU, in the Canadian Arctic present an opportunity to examine annual winter snow accumulation measurements dating back to 1960. An ice shaft excavated in 1961-1962 on the nearby Müller Ice Cap and the analysis of summer and winter accumulation horizons allows for the extension of this record further 40 years to 1920. This study examines the accumulation history on Axel Heiberg Island, discusses the challenges associated with comparing records of different origin, and considers potential future steps to improve snow accumulation monitoring in a polar desert environment.

Authors: *Katrine Trottier, Michel Baraër, Daniel Nadeau*

Using High-Frequency GPR as a Non-Destructive Method to Monitor Liquid Water Content and Hydrological Behaviour During Rain-on-Snow Events in Contrasting Eastern Canadian Environments

Understanding the response of seasonal snowpacks to mid-winter melt and rain-on-snow (ROS) events remains essential for improving cold-region hydrological models. Yet, internal liquid water content (LWC) dynamics are still poorly constrained due to the lack of continuous, high-resolution, non-invasive measurements. This study presents a fixed-station, high-frequency ground-penetrating radar (GPR) approach as a non-destructive method to monitor LWC and hydrological behaviour in snowpacks across two climatically contrasting watersheds in Québec, Eastern Canada (45°N and 47.3°N), during the 2024–2025 winter season.

The first site, Sainte-Marthe (45°N), is a lowland agricultural watershed (10 km²) located at approximately 110 m above sea level, characterized by ephemeral snow cover and frequent mid-winter melt and ROS events. The second site, Montmorency Forest (47.3°N), is a boreal watershed (66 km²) at 670 m elevation, where a deep, persistent snowpack typically accumulates from November to May. GPR systems with 1500 MHz antennas were installed at Sainte-Marthe, while 500 MHz antennas were used at Montmorency to enhance penetration into the thicker snowpack. Vertical radar profiles were recorded at sub-hourly intervals, enabling centimetric-scale resolution of internal snowpack dynamics. Metrics such as amplitude attenuation, two-way travel time (TWT), and velocity-derived dielectric permittivity (Bradford et al., 2009) were used to estimate LWC.

Snow pit measurements, including density, stratigraphy, temperature, and LWC (using an A2 dielectric probe), were collected for validation. Time-lapse terrestrial LiDAR scanning was also employed to quantify surface lowering and volumetric snowpack change.

Preliminary results show strong radar signal attenuation during ROS events, especially in the lower snowpack layers where liquid water accumulates above stratigraphic boundaries. Ice layers play a critical role in modulating percolation by acting as semi-impermeable barriers, leading to temporary water retention and lateral flow. These layers generate distinct and evolving radar reflections, highlighting dielectric discontinuities that trace the movement and storage of water within the snowpack. At Sainte-Marthe, ROS events result in rapid wetting front propagation, significant amplitude losses, and shortened TWTs, indicating early and dynamic meltwater outflow. In contrast, the snowpack at Montmorency shows delayed radar responses, consistent with stronger stratification, lower temperatures, and increased water retention.

This fixed GPR framework provides a novel, high-resolution, non-destructive method to monitor snowpack hydrological processes in real time, offering new insights to improve the representation of melt and ROS events in snow models and hydrological forecasting systems.

Authors: *Baxter Vieux, Jean Vieux, and William Vieux*

Weather Radar for Improved SWE Monitoring at Watershed Scales

Accurate measurement of snow water equivalent (SWE) is fundamental for water resource management and reliable streamflow prediction in snow-dominated regions worldwide. Conventional SWE monitoring technologies are constrained by limited spatial and temporal resolution or high operational costs, creating gaps in data coverage that hinder effective decision-making. Recent advances in dual-polarization weather radar and machine learning now offer new opportunities to enhance SWE assessment at watershed scales.

This study introduces SnowQ (patent pending), a comprehensive framework that integrates dual-polarization radar observations with machine learning algorithms trained and validated using high-resolution airborne LiDAR and satellite synthetic aperture radar (SAR) snow depth datasets. Ground-based sensors provide crucial snow density measurements, supporting the conversion of remotely sensed snow depth to SWE and ensuring robust model calibration and validation.

The SnowQ approach incorporates persistent spatial patterns of snow deposition and surface modification processes, enabling more accurate conversion of radar-measured atmospheric ice water content to SWE accumulated at the surface. By explicitly accounting for the influences of sublimation, melting, wind transport, and topography, SnowQ reliably transforms snapshots of SWE from LiDAR into continuous, hourly watershed-scale SWE maps. This physics-guided machine learning system delivers significant improvements in SWE monitoring frequency and accuracy, offering scalable, cost-effective solutions for operational snowpack assessment in complex mountain environments.

Overall, SnowQ advances SWE measurement technology by bridging critical gaps between airborne, satellite, and ground-based observations—providing actionable information for streamflow forecasting and water management in snow-dependent communities worldwide.

Authors: *Nicolas R. Leroux, Vincent Vionnet, Courtney Bayer, Julien Meloche, Marco Carrera, Bernard Bilodeau, Franck Lespinas, Maria Abrahamowicz, Arlan Dirkson, Mark Buehner, Benoit Montpetit, and Chris Derksen*

Assimilation of synthetic radar backscatters at Ku-band improves SWE estimates

In cold regions, snow serves as the primary water source for downstream rivers and lakes. Accurate gridded estimates of Snow Water Equivalent (SWE) are hindered by the sparse ground observation network and the low resolution of satellite passive microwave products. To address this, Environment and Climate Change Canada, the Canadian Space Agency and Natural Resources Canada are developing the Terrestrial Snow Mass Mission (TSMM), a dual Ku-band satellite that will measure weekly backscatter at 13.5 GHz and 17.25 GHz over the Northern Hemisphere at 500-m spatial resolution. This study uses a synthetic experiment to assess the feasibility of assimilating Ku-band backscatter to improve SWE estimates. We used the snowpack model Crocus implemented in the Soil-Vegetation-Snow v2 (SVS2) land surface model and coupled with the Snow Radiative Transfer Model (SMRT) model. SVS2/Crocus and SMRT are implemented in the Multiple Snow Data Assimilation System (MuSA) to carry out data assimilation experiments. Observations extracted at weekly intervals from the synthetic truth (SWE and backscatter) were assimilated with a particle filter in point scale at three sites spanning different Canadian climates (Arctic, Alpine, continental humid) over three winter seasons. Meteorological forcing derived from the high-resolution Canadian meteorological model was perturbed to generate ensembles of snow simulations for assimilation. Results indicate that assimilating backscatter observations reduced the root mean square error of SWE estimates by up to 45 % at the Arctic and continental humid sites compared to the open-loop ensemble, performing similarly to the assimilation of SWE with an observation error larger than 20 %. Assimilating backscatter observations at the Alpine site only improved the SWE estimates by ?10 % when assimilating the difference of the two backscatter observations but showed no improvements when assimilating the backscatter observations individually. Assimilating backscatter and SWE observations also improved the simulated vertical profiles of snow density and specific surface area. These findings demonstrate the potential of direct Ku-band backscatter assimilation to enhance both bulk SWE and snowpack property estimates.

Authors: *Vincent Vionnet, Julien Meloche, Nicolas R. Leroux, Kevin Fourteau, Benoit Montpetit, Kate Hale and Chris Derksen*

A new snow metamorphism scheme in Crocus improves simulations of SSA and radar backscatters in northern environments

The current development of spaceborne radar missions to retrieve snow water equivalent (SWE) requires state-of-the-art modeling systems able to provide accurate estimation of snow properties (including its microstructure) across large areas. In this context, the Soil Vegetation and Snow v2 (SVS2) model has been recently developed at Environment and Climate Change Canada. It includes the detailed snowpack model Crocus with enhanced parameterizations to simulate snowpack properties across Canada. Recent evaluations in northern environments have nonetheless highlighted persistent limitations in the Crocus semi-empirical snow metamorphism scheme leading to strong underestimations of snow specific surface area (SSA) that negatively impact simulated radar backscatters. To address this limitation, the physically-based equation for SSA evolution of Braun et al. (2025) has been implemented in SVS2/Crocus. Coefficients for isothermal and temperature gradients conditions used in the formulation of Braun et al. (2025) have been adjusted using measurements of SSA evolution taken from multiple controlled cold-laboratory experiments published in the literature. We then evaluated SVS2/Crocus and its revised snow metamorphism scheme using snow measurements from the 2023 NASA SnowEx Campaign in Alaska to assess model performances in simulating northern snowpack properties. SVS2/Crocus was run at 500-m resolution for winter 2022/23 over two domains covering tundra and boreal forest environments in Alaska. The simulations were driven by downscaled atmospheric forcing from the latest version of the Canadian Surface Reanalysis. Data from snow pits (including snow penetrometer measurements) collected at multiple sites during the SnowEx campaign were used to evaluate the model. The original metamorphism scheme significantly underestimated SSA values throughout the entire snow profile. In contrast, the revised scheme delivered better SSA simulations across boreal forest and tundra locations, with ongoing challenges limited to the bottom layers of tundra snowpacks where depth hoar formation in Arctic conditions remains poorly represented. This work contributes to the development of a new snow modelling system required to support SWE product development for the Terrestrial Snow Mass Mission (TSMM) under development in Canada.

Authors: *John Mohd Wani, Kelly E. Gleason, Matteo Dall'Amico, Federico Di Paolo, Stefano Tasin, Gaia Roati, Marco Brian, Francesco Tornatore, and Riccardo Rigon*

Three decades of snow water equivalent dynamics in the Po River Basin, Italy: Trends and Implications

Seasonal snowpack is a key component of the mountain cryosphere, acting as a natural reservoir that regulates downstream runoff. In mid- and low-elevation regions such as the European Alps, this critical water resource is highly vulnerable to ongoing climate change. In this study, we analysed a high-resolution (500x500m), 30-year (1991-2021) daily dataset of snow water equivalent (SWE) in the Po River District to understand how its snow dynamics are changing. This data was generated using the "J-Snow" modeling framework, which integrates the physically based GEOtop model with in-situ snow depth observations and earth observation snow cover products such as MODIS. To assess changes in SWE dynamics over time, we selected six snow phenology metrics for each hydrological water year. The metrics were selected based on their relevance in characterizing either snow water volume or snow duration. The three snow volume metrics include Maximum SWE (MaxSWE), April 1 SWE (April1SWE) and Snow Water Storage (SwS), while, the snow duration metrics include SWE Duration (SWEduration), Day of Year of Max SWE (MaxSWE.dowy) and Snow Disappearance Date (SDD). Our results reveal significant spatiotemporal variability in snowpack dynamics, including snow accumulation patterns, peak SWE timing, and snow disappearance dates and a strong elevation-dependent change in the snow regime. Additionally, elevation-wise statistical analysis of snow volume and duration metrics shows that the most pronounced changes occur below 2000 m a.s.l. Below this threshold, both snow volume metrics and duration metrics show a significant decrease, indicating earlier and reduced accumulation. Above this elevation, the snow volume metrics show increasing trend (needs verification) while as the duration metrics continue to show a shortened (decreasing trend) snow season except at the highest elevations (>2500 m). The findings of this study highlight the changes in the hydrological regime of the Po River District, with significant implications for water availability and management under ongoing climate change.

Authors: *Celine Anderson, Duanne White, Cath Hughes, Leah Moore*

Snowmelt contributions to groundwater recharge and streamflow discharge at a hillslope scale in the Australian Snowy Mountains

Snow cover in Australia is confined primarily to the alpine regions of south-eastern Australia, particularly the Snowy Mountains, New South Wales. Here, marginal snowpack conditions are highly vulnerable to a changing climate, providing an ideal location to examine the impacts of a rapidly diminishing snowpack on groundwater recharge and streamflow generation.

The Snowy Mountains Australian Mountain Research Facility (AMRF) hillslope sites provide a valuable framework to investigate the influence of snow on the local hydrological cycle and assess potential climate change impacts at a sub-catchment functional level, where hillslope-scale hydrology determines connectivity and water fluxes between upland snowpack environments and downstream waterways.

Three AMRF hillslope sites have been instrumented with hydrological monitoring arrays since 2021. In addition to the physical hydrological measurements, three years of monthly rainwater, groundwater, surface water, and snowpack samples have been collected and analysed for stable isotope and hydrogeochemical analysis. Results reveal that despite year-round precipitation, groundwater recharge in these alpine catchments predominantly occurs during winter, coinciding with seasonal snowpack accumulation, with limited recharge present throughout the warmer late spring to autumn periods. The lack of variability in groundwater isotope signatures provides a unique opportunity to look more closely at stream hydrograph behaviour during snowmelt and the relative contributions of groundwater, rainwater and snowmelt in streamflow generation.

A recent intensive field campaign examining isotopic composition of rainfall, snowfall, snowpack, snowmelt, and streamflow has provided a more detailed insight into the complex pathways by which snowpack transitions into snowmelt, infiltrates to recharge groundwater or subsurface stores, and subsequently contributes to streamflow. These results highlight the contribution and importance of snow in current hydrological response patterns experienced across the Snowy Mountains. Creating insights into what we may see into the future as the climate warms and snowpack conditions decline.

Authors: *Duanne White, Celine Anderson, Phil Campbell, Sarah Thompson, Natasha Harvey, Justin Mann*

Ripening and melt processes in marginal Australian snowpacks

While the radiative fluxes that provide energy for snowmelt in marginal snowpacks are relatively well studied, significant questions remain around the role the of internal snowpack dynamics of melt rates. In colder regions, the 'ripening' of the snowpack that is the precursor to significant melt and runoff is often the transition from cold to warm snow. However, temperatures within the marginal and maritime snowpacks are generally at or near the melting point through most of the winter, potentially facilitating melt events throughout the snow season.

Here, we describe snowpack measurements from marginal snowpack sites in the Australian Alps that have been instrumented and regularly monitored as part of the Australian Mountain Research Facility. Measurements of snow thickness, structure, temperatures, liquid water content and shortwave transmission through the snowpack have been monitored at four alpine and subalpine hillslope sites during the 2024 and 2025 austral winters, along with local radiative flux, soil moisture and groundwater storage, meltwater outflows as part of the Australian Mountain Research Facility hydrological arrays.

Results to date indicate that even in colder alpine sites, the snowpack is dynamic throughout both winter and spring, with snow ripening occurring throughout the winter in between snow deposition events. In winter rain on snow events frequently contribute liquid water through to the base of the snowpack. While these winter events are generally too cold to contribute to melt, they contribute to ripening through changes in grainsize, form and shortwave transmission extinction coefficients. Sensible heat transfer also contributed to ripening, with transmission though metre deep snowpacks also frequently occurring via during strong, warm north-westerly wind events, which contribute to both melt and grainsize changes. These mid-winter ripening processes also contribute to a strongly fluctuating shortwave albedo, which in between snowfall events can reach springtime values even in the middle of winter. Thus, the transition from an accumulating to melting snowpack in this region is generally very quick once snowfalls cease and shortwave input increases into spring, contributing to rapid increases in stream discharge.

Authors: *Pau Wiersma, Jessica Lundquist, Jan Magnusson, Nadav Peleg, Bettina Schaefli, Grégoire Mariéthoz*

Can streamflow observations constrain SWE reconstructions? Lessons from idealized experiments

Streamflow observations contain information on melt volume and timing, and can therefore theoretically help quantify pre-melt SWE properties. However, the melt information is both delayed and diluted, and to date no methodology exists to extract it for the purpose of constraining SWE reconstructions.

We introduce an inverse hydrological modeling framework for streamflow-constrained SWE reconstruction. In a series of idealized experiments, we assess the constraining potential of streamflow across different catchments, climates, degrees of uncertainty, and combinations of streamflow and SWE performance metrics. The lessons drawn from these idealized experiments will inform us on when, where, and how streamflow-constrained SWE reconstruction is most feasible in the real world.

Authors: *Maiju Ylönen, Hannu Marttila, Joschka Geissler, Anton Kuzmin, Pasi Korpelainen, Timo Kumpula, Pertti Ala-Aho*

UAV LiDAR surveys and machine learning improves snow depth and water equivalent estimates in the boreal landscapes

Northern regions are warming at a faster rate than the global average, resulting in notable changes in snow depth and snow water equivalent (SWE). To better understand local-scale variability in snow distribution and properties, accurate methods are needed to bridge the gap between satellite observations and point-scale measurements. In this study, we mapped snowpack development at two sites in northern Finland during the winter season of 2023-2024 using unmanned aerial vehicles (UAVs) with light detection and ranging (LiDAR) technology. UAV flights were conducted four times during the winter to capture the snow distribution from the early stage to the melting phase. Snow depth maps generated from these flights were integrated with monthly snow course measurements and daily snow depth reference data as an input for a clustering-based machine learning model, ClustSnow (Geissler et al. 2023). The ClustSnow workflow produces high-resolution (1m) daily snow depth and SWE maps for study areas. Root mean square error (RMSE) values for SWE range from 31 to 36 mm when compared to manual measurements from snow course data, demonstrating that the model's accuracy in capturing snow dynamics and spatial variability. To assess the influence of vegetation on the snow depth distribution, the study areas were categorized into three clusters: forested areas, transition zones with low vegetation or forest gaps, and open areas. Our analysis suggests, that these clusters can be extended to model SWE subsequent years, without the need for new UAV LiDAR surveys. This study underscores the role of vegetation and landscape characteristics in snow accumulation and melt processes, particularly in the Arctic boreal zone. The findings enhance the spatio-temporal accuracy of snow monitoring and offer valuable tools for hydrological modeling and satellite data validation.