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SnowHydro 2020
International Conference on Snow Hydrology Challenges in Mountain Areas

28th – 31st January 2020
Eurac Research, Bolzano/Bozen, Italy

ABSTRACT BOOK

SnowHydro 2020

International Conference on Snow Hydrology

Challenges in Mountain Areas

28th – 31st January 2020, Bolzano/Bozen, Italy

Responsible organizers

Claudia Notarnicola – EURAC Research (Italy) – Scientific coordinator

Giacomo Bertoldi – EURAC Research (Italy) – Scientific advisor

María José Polo – University of Cordóba (Spain) – Scientific advisor

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Paola Winkler - EURAC Research (Italy) – Project manager

Venue

EURAC, lecture room “Auditorium”.

Welcome to the SnowHydro Conference in Bolzano/Bozen 2020

Snow is a dynamically changing water resource that plays an important role in the hydrological cycle in mountainous areas. Snow cover contributes to regulate the Earth surface temperature, and once it melts, the water helps fill rivers and reservoirs in many regions of the world.

In terms of spatial extent, seasonal snow cover is the largest single component of the cryosphere and has a mean winter maximum areal extent of 47 million square kilometers, about 98% of which is located in the Northern Hemisphere. While on large scale snow cover changes affect the energy exchange between Earth's surface and the atmosphere and are, thus, useful indicators of climatic variation, on a smaller scale, variations in snow cover can affect regional weather patterns. Therefore, snow cover is an important climate change variable because of its influence on energy and moisture budgets.

The strong consequences of changes in snow amount on Earth's environment and population, have led scientists to develop ways for continuously measuring and monitoring snow and its properties.

The traditional snow observations consist of in situ measurements during periodic field campaigns at fixed sites or through automatic nivological stations network recording snow parameters and often are coupled to weather stations. In mountain regions, where the spatial variability of the snow cover is particularly high due to the complex topography, the related hydrological processes are mostly unknown because of the lack of spatially and temporally continuous observations. To fill this gap, remote sensing can make a valuable contribution by providing higher spatial and (often) temporal resolution data with respect to ground measurements. However, remotely sensed data are often biased by snow misclassifications and cloud cover frequently limits the availability of snow related information. A consolidate method for retrieving information about snow characteristic is the application of distributed, numerical hydrological models, which have been already applied at different scale. Even though extensively tested, these models can be subjected to rather large uncertainties if used in spatially distributed applications, especially in mountainous regions. These uncertainties may be originated mainly from uncertainties in the meteorological input data that have often a limited availability in mountainous areas and in snowpack process representations, especially in melting season.

The SnowHydro conference will address the range of topics regarding snow, its significance for hydrology and its impact on climate change. The main objective is to bring together experience from experimental research, hydrological modelling and remote sensing to facilitate joint research on snow science.

The organizing committee welcomes you to Bolzano/Bozen and we wish you a stimulating and enjoyable conference in South Tyrol!

The organizing committee

We gratefully acknowledge the support of our partners and sponsors

Green Event

Sustainability is not just a modern term to use, but a responsibility. As we all have an impact on the environment, we want to provide you an event as green as possible. We are proud to tell you that the conference will be certified Green Events to keep the environmental impact as low as possible. We further encourage everyone to use public transportation. We recommend you to get a Mobilcard, which can be used, with all buses, trains and several cable cars. Ask for it in your hotel.

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Conference Program Overview

Tuesday, January 28th

08.00 – 09.00 Registration and poster set-up

Lecture room "Auditorium"

09.00 – 09.10	**Welcome and introduction** Claudia Notarnicola, Institute for Earth Observation, Eurac Research
09.10 – 09.20	**Welcome address** Roland Psenner, Eurac Research President
09.20 – 09.30	**Welcome address** Roberto Dinale, Civil Protection Agency, Autonomous Province of Bolzano – South Tyrol

09.30 – 10:00	**Keynote lecture** **"Monitoring snow using satellite data"** Thomas Nagler, *Enveo IT (Austria)*

Snow Remote Sensing **Session 1: Snow cover dynamics - temporal and spatial variability** Chairperson: Jeffrey S. Deems	
10.00 – 10.15	**Estimation of temporal changes of snow water equivalent by SAR interferometry using Sentinel-1 data in a snowfield in Trentino** Delia Marzari et al.
10.15 – 10.30	**Homogenization and analysis of mean seasonal snow depth time series** Gabriele Chiogna & Giorgia Marcolini
10.30 – 10.45	**Combining COSMO-SkyMed data and machine learning for SWE monitoring in alpine areas** Emanuele Santi et al.

10.45 – 11.15	Coffee break, foyer Auditorium

Session 2: Snow cover dynamics- temporal and spatial variability Chairperson: Rafael Pimentel	
11.15 – 11.30	**Multi-sensor wet snow mapping using wide-area radar backscatter composites** David Small et al.
11.30 – 11.45	**Monitoring snow cover and snow phenology dynamics in global mountain areas by using MODIS images from 2000 to 2018** Claudia Notarnicola
11.45 – 12.00	**Changes in Andes snow cover from MODIS data, 2000–2016** Freddy Saavedra et al.
12.00 – 12.15	**Snow cover analysis integrating satellite and terrestrial imageries over a decade** Roberto Salzano et al.
12.15 – 12.30	**A combined Terra/Aqua MODIS snow-cover product for the High Mountain Asia between 2002 and 2018** Sher Muhammad

12.30 – 13.30	Lunch, foyer Auditorium

Poster session – Room: Conference hall **Snow remote sensing & experimental research** Chairperson: Mattia Callegari	
13.30 – 14.00	Poster presentation (2 min for each poster) **Snow cover evolution in the Swiss Alps using Earth Observation Data Cube** Charlotte Poussin **Standardized Snow Pack Index (SSPI) in the Piave river basin** Mauro Valt & Giovanni Onofrio **Modelling spatio-temporal dynamics of snow depth and large herbivore's winter habitat selection** Emanuele Cordano et al. **Snow bias in EURO-CORDEX regional climate models and its dependence on topography mismatch and cold bias in the European Alps** Michael Matiu et al. **Estimating Multiscale Snow Cover Variability in the South of Western Siberia: SSSC Project framework** Dmitry Pershin **Hom4Snow: Homogenization of snow measurements for robust socio-economic Snow climate indicators in the Alps** Gernot Resch et al. **Monitoring the snow pack internal stress by lineament domain analysis** Paola Cianfarra & Mauro Valt **Theia Snow collection: high-resolution operational snow cover maps from Sentinel-2 and Landsat-8 data** Simon Gascoin et al. **GNSS-based monitoring of snow water equivalent and snow liquid water content in different regions and altitudes and potential (snow)hydrological applications** Franziska Koch et al. **Evaluating the trends of the Degree-Day Factors in the high-altitude regions** Muhammad Fraz Ismail et al. **A seasonal field campaign on the Hochjochferner glacier (South Tyrol) exploiting ablation stakes and the Terrestrial Laser Scanner. Challenges, benefits and comparison with modelling** Nicola Di Marco et al.
14.00 – 15.00	Poster session. All authors are available at poster location for discussion.

Session 3: Remote Sensing of Snow Properties Chairperson: Gabrielle J.M. De Lannoy	
15.00 – 15.15	**Enabling the next generation of water management with the Airborne Snow Observatory** Jeffrey Deems et al.
15.15 – 15.30	**Multi-platform, multi-sensor snow surface properties for energy balance and model validation** Karl Rittger
15.30 – 15.45	**Monitoring snow properties and snowmelt using thermal inertia** Roberto Colombo et al.
15.45 – 16.00	**Development of a novel approach for snowmelt monitoring in alpine areas by using multi-temporal and multi-sensor remote sensing imagery** Valentina Premier et al.
16.00 – 16.15	**A new era of remote sensing to constrain physically-based snow hydrologic modeling: Imaging spectroscopy of snow physical properties** Thomas Painter

16.15 – 16.45	Coffee break, foyer Auditorium

Session 4: Remote Sensing of Snow Properties Chairperson: Emanuele Santi	
16.45 – 17.00	**Snow parameters estimation through new data fusion approaches involving a hydrological model and remote sensing products** Ludovica De Gregorio et al.
17.00 – 17.15	**Monitoring snow water in mountain areas of Northern Sweden: performance evaluation of satellite/modelled snow products and exploration of microwave brightness temperature for characterizing snow accumulation/ablation** Jie Zhang et al.
17.15 – 17.30	**Snow depth variability in the Northern Hemisphere mountains observed from space** Gabrielle J.M. De Lannoy et al.
17.30 – 17.45	**Suitable digital elevation model spatial resolutions for structure-from-motion snow depth mapping in mountain areas** Jason Goetz & Alexander Brenning

18.00 – 19.15	Icebreaker (Eurac) - foyer Auditorium
19.15 – 20.15	Guided city tour: we start from Eurac for a stroll through the historic city center

Wednesday, January 29th

Lecture room "Auditorium"

08.30 – 09.00	**Keynote lecture** **"Snow hydrological modelling and observations for the hydropower industry in the deregulated Nordic energy market"** Jan Magnusson, *Statkraft AS, Oslo (NO)*

Snow Hydrology and Modelling **Session 1: Progress in simulating snow processes and model evaluation** Chairperson: Tobias Jonas	
09.00 – 09.15	**Snow management with physically based snowpack models for Alpine ski resorts: the PROSNOW project** Carlo Carmagnola et al.
09.15 – 09.30	**Process-based simulation of snow cover evolution in ski resorts with AMUNDSEN: first results from the PROSNOW project** Florian Hanzer et al.
09.30 – 09.45	**Sensitivity of snow models to the accuracy of meteorological forcings in mountain environment** Silvia Terzago et al.
09.45 – 10.00	**Efficient multi-objective calibration and uncertainty analysis of distributed snow simulations in rugged alpine terrain** James Thornton et al.
10.00 – 10.15	**Snow water equivalents exclusively from snow heights and their day-to-day changes** Michael Winkler et al.

10.15 – 10.45	Coffee break, foyer Auditorium

Session 2: Progress in simulating snow processes and model evaluation Chairperson: Giacomo Bertoldi	
10.45 – 11.00	**Validation of ERA-5 snow water equivalent reanalysis over the Upper Adige River Basin (Italy)** Susen Shrestha et al.
11.00 – 11.15	**Monitoring and simulating snow accumulation on the lowest perennial ice field of the Alps** Michael Warscher et al.
11.15 – 11.30	**Multi-level spatiotemporal validation of hydroclimatological modeling results in mountain areas: method and data collection** Ulrich Strasser et al.
11.30 – 11.45	**Parameter uncertainty assessment for a conceptual hydrological model in a snow-dominated catchment combining streamflow records and MODIS snow cover maps** Nicola Di Marco et al.
11.45 – 12.00	**SNOW4 - An Operational Model for Precipitation Supply Forecasts** Uwe Böhm & Gerold Schneider

12.00 – 13.00	Lunch, foyer Auditorium

Poster session – Room: Conference hall **Progress in simulating snow processes and model evaluation & Snow-Atmosphere Interface** Chairperson: Carlo Marin	
13.00 – 13.30	Poster presentation (2 min for each poster) **The effects of forest cover on snow water equivalent-Results from the "5th SWE intercomparison"** Rudi Nadalet et al. **Snow duration in forests after low to moderate severity burn: Does tree size matter?** Michaela Teich et al. **Snow Cover Area (SCA) changes over semi-arid region using CMIP5 Multi-model Ensemble (Case study: Uremia lake basin, Iran)** Maral Habibi et al. **Multi-year evaluation of a distributed data-assimilation snow model (S3M v 3.1) and implications for hydropower-hydrologic modeling** Francesco Avanzi et al. **Assimilation of snow depth maps from satellite photogrammetry in Crocus in distributed geometry** César Deschamps-Berger et al. **Exploiting machine learning techniques for monthly runoff prediction in a mountain basin in the Andes range** Sofia Teverovsky et al. **Water availability forecasting of the Tien-Shan Rivers for different periods using remote sensing data** Olga Kalashnikova & Abror Gafurov **Does a shift in precipitation from snow towards rain lead to a decrease in mean streamflow? - Comparison of MOPEX Dataset and CAMELS Dataset** Lina Wang & Ross Woods **Quantification and vizualization of changes in runoff timing and changes in runoff seasonality in snow-dominated river basins** Erwin Rottler et al. **Historical reanalysis of the snow water equivalent in Trentino** Paolo Tranquillini et al. **Past and future trends in snow water equivalent along an alpine slope** Reinhard Fromm et al. **Towards a high-resolution long-term snow climatology for Germany** Uwe Böhm & Gerold Schneider
13.30 – 14.30	Poster session. All authors are available at poster location for discussion

Session 3: Cryospheric processes - observations and modelling Chairperson: Ulrich Strasser	
14.30 – 14.45	**The state of Art of Modelling Permafrost and Freezing Soil** Niccolò Tubini & Riccardo Rigon
14.45 – 15.00	**Canopy structure controls on energy fluxes to the forest snowpack: observations and modelling** Tobias Jonas et al.
15.00 – 15.15	**Impact of snowfall distribution on the assimilation of passive microwave data in a snowmelt runoff prediction model** David Gustafsson et al.
15.15 – 15.30	**The influence of snow patch size on local-scale advection of sensible heat towards a patchy snow cover** Luuk van der Valk et al.

15.30– 16.00	Coffee break, foyer Auditorium

Session 4: Snow in semi-arid environment Chairperson: Lucas Menzel	
16.00 – 16.15	**A 55-yr trend analysis of snow torrentiality and aridity in a Mediterranean mountain range, Sierra Nevada, Spain** María José Pérez-Palazón et al.
16.15 – 16.30	**Process-oriented streamflow characterization in mountain rivers of semiarid areas: Sierra Nevada, Spain** Pedro Torralbo et al.
16.30 – 16.45	**Can we learn from "snow islands" about future trends in different snow regions in the world?** María J. Polo et al.

18.00 – 19.00	Public event with the participation of the meteorologist Luca Mercalli (Auditorium)
19.30 –	Conference dinner (Eurac) - foyer Auditorium

Thursday, January 30th

Lecture room "Auditorium"

08.30 – 09.00	**Keynote lecture** **"The effect of changes in snow seasonality on hydropower"** Miriam Jackson, *Norwegian Water Resources & Energy Directorate (NO)*

Snow-Atmosphere Interface **Session 1: Prediction of snow melt and run-off** Chairperson: María J. Polo	
09.00 – 09.15	**Comparison of SWE at basin scale with measured discharge at basin outlet by separating the contribution of rainfall and snowfall** Matteo Dall'Amico et al.
09.15 – 09.30	**Protective function of the snowpack during rain-on-snow events** Roman Juras et al.
09.30 – 09.45	**A physics-based approach for efficiently parameterizing turbulent heat fluxes during rain-on-snow in support of operational, probabilistic melt forecasts** Adam Winstral & Tobias Jonas
09.45 – 10.00	**Influence of input data sources on SRM seasonal snowmelt runoff prediction** Wolfgang Bogacki & Muhammad Fraz Ismail
10.00 – 10.15	**Qualification of an operational snowmelt model against a composite dataset** Jean-Loup Hannebicq et al.

10.15 – 10.45	Coffee break, foyer Auditorium

Session 2: Prediction of snow melt and run-off Chairperson: Miriam Jackson	
10.45 – 11.00	**Understanding runoff generation processes in meltwater-dominated catchments by means of stable water isotopes** Giulia Zuecco & Daniele Penna
11.00 – 11.15	**The role of snowmelt to stream flow: a tracer-based hydrograph separation of the Sulden River in South Tyrol** Michael Engel et al.
11.15 – 11.30	**Challenges for the use of seasonal forecasts in Mediterranean mountain areas** Javier Herrero et al.
11.30 – 11.45	**SWE modelling for the optimisation of hydropower production in alpine catchments** Paolo Pogliotti et al.
11.45 – 12.00	**Assessment of water resources of the Amudarya river zone of runoff formation by remote sensing methods** Jafar Niyazov et al.

12.00 – 13.00	Lunch, foyer Auditorium

Poster session – Room: Conference hall	
13.00 – 14.00	Poster session. All authors are available at poster location for discussion

Session 3: Climate change, snow conditions and water supply Chairperson: Marc Zebisch	
14.00 – 14.15	**Changes in snow cover over Central European low mountain ranges** Lucas Menzel & Chunyu Dong
14.15 – 14.30	**Snow cover dynamics in the Pamir and Tianshan mountains and its attribution to climate change** Abror Gafurov et al.
14.30 – 14.45	**Widespread and accelerated decrease of mean and extreme snow depth over Europe** Adrià Fontrodona-Bach et al.
14.45 – 15.00	**Can climate models represent the snow occurrence in semiarid areas? The example of Sierra Nevada Mountain Range** Rafael Pimentel et al.
15.00 – 15.15	**Snow precipitation trends in the Adige valley: a citizen's science dataset** Giacomo Bertoldi et al.

15.15 – 15.45	Coffee break, foyer Auditorium

Session 4: Climate change, snow conditions and water supply Chairperson: Abror Gafurov	
15.45 – 16.00	**Long-term (1900-2100) SWE and Hydrometeorological reconstructions in the French Southern Alps (Durance watershed and Mercantour Natural Parc)** Thibault Mathevet
16.00 – 16.15	**The impact of climate-change induced alteration of snow and glacier processes on solar-hydropower complementarity in Alpine basins** Handriyanti Diah Puspitarini et al.
16.15 – 16.30	**Snow reliability and alpine ski sport in Germany** Uwe Böhm et al.
16.30 – 16.45	**Snow Monitoring for Water Availability and Irrigation – contributions within H2020 Extreme Earth** Florian Appel
16.45 – 17.15	**Main highlights of the conference - IPCC contribution** Claudia Notarnicola
17.15 – 17.30	**Conclusive remarks & Winner announcement**

Main highlights from the conference - IPCC Contribution: "Mountain perspectives on snow: combining ground observations and remote sensing with modelling and scenarios of future climate"

The main aim of this contribution is to provide an overview of the conference highlights in terms of the main scientific advances and knowledge gaps. This contribution will be made available to all participants. If feasible, a publication, in peer-reviewed scientific journal(s), can be considered as a further development, taking particular care to note the IPCC WGII's cut-off dates for submission (1st July 2020) and accepted (1st May 2021) publications (www.ipcc.ch).

Abstracts of the conference

Snow Remote Sensing

Session 1: Snow cover dynamics - temporal and spatial variability

Estimation of temporal changes of snow water equivalent by SAR interferometry using Sentinel-1 data in a snowfield in Trentino

Delia Marzari[2], Matteo Dall'Amico[1], Nicolò Franceschetti[1], Alfonso Vitti[2].

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2 Università di Trento, Dipartimento di ingegneria civile ed ambientale, Via Mesiano 77 Trento

Abstract:
SWE monitoring is very important for many users and field areas, like hydrology, human activities (tourism, civil engineering) and prediction of natural disasters like flood and avalanches. Ground-based SWE measurements are insufficient or in some areas completely lacking and therefore the interpolation of few isolated SWE observations may lead to significant uncertainty at basin scale.
Spaceborne passive microwave sensors combined with ground-based stations data represent one of the current used method used to generate daily estimates of SWE (Jindrova et al., 2017). However, passive microwave sensors present some important limitations, especially in case of cloud cover when passive sensors cannot imagine the ground. Furthermore, they have difficulties in detecting both deep and shallow snow depth (2) and they can only detect wet snow (Jindrova et al., 2017).
Spaceborne SAR (synthetic aperture radar) sensors represent an interesting alternative, less sensitive to limitations of technologies based on passive micro-waves sensors. Satellite SAR missions can provide high-resolution data, at a few tens of meters spatial resolution, that can be exploited for SWE mapping in all weather conditions and on a very high frequency base thanks to satellite revisit time and to the sensor capability to acquire data on a day-and-night mode. Moreover, SAR sensors allow SWE monitoring even in areas with dry snow. SAR data comprise amplitude and phase measurements: amplitude is the strength of the radar response and phase is the fraction of one complete sine wave cycle. In this work we use the phase information adopting a differential interferometry technique to map the temporal variations of SWE. The microwaves of the SAR signal interact with the snow volume by absorption, scattering, and refraction. According to Leinss et al. (2015), we can consider absorption and scattering negligible and just consider refraction. The shift in phase observations caused by changes in the waves refraction may be isolated and exploited to generate maps of temporal variation of SWE from SAR interferograms.
In this work we apply this methodology on a study area in Trentino where many SWE field observations are available. The results of SWE maps deriving from the processing of SAR data are compared with the ones obtained by the physically based approach proposed by Dall'Amico et al (2018).

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Dall'Amico, M., Endrizzi S. and Tasin S. (2018), Mysnowmaps: operative high-resolution real-time snow mapping, Proceedings of the International Snow Science Workshop, Innsbruck, 328-332. Disponibile su: http://arc.lib.montana.edu/snow-science/objects/ISSW2018_O04.7.pdf

Jindrova, M., Bauzà Llinàs, J., Zabla Torres, A., TASK 3: CONTINUATION OF SNOW & ICE TASK. D 3.2: Summary Report to Support EEA, version 1.0, 2017.

Leinss, s., Wiesmann, A., Lemmetyinen, J., Hajnsek, I. Snow Water Equivalent of Dry Snow Measured by Differential Interferometry, Journal Selected Topics in Applied Earth Obs. and Remote Sens., 2015.

Homogenization and analysis of mean seasonal snow depth time series

Gabriele Chiogna[1,2], Giorgia Marcolini[1]

1 Technical University of Munich, Munich, Germany
2 University of Innsbruck, Austria

Snow depth and snow cover duration time series are valuable sources of information for several disciplines including hydrological and climate studies. Long and accurate time series of snow depth measurements are rare, and their analysis should be cautious. We show that breakpoints can be detected in mean seasonal snow depth time series using the Standard Normal Homogeneity Test. Such breakpoints have different causes, such as changes in the operator and in the measurement equipment as well as in the displacement of the station. It is not always possible to identify the causes of such abrupt changes in the behavior of the time series, since metadata are not always available. Moreover, even when metadata are available, the occurrence of the aforementioned changes does not necessarily imply the occurrence of a breakpoint. Therefore, it is important to develop robust mathematical methods for breakpoint detection in mean seasonal snow depth time series. The occurrence of these breakpoints in fact influences the analysis of the time series, such as the identification of anomalies and trends. Datasets collected in Italy and in Austria show the relevance of considering that mean seasonal snow depth time series can be affected by breakpoints, highlighting that homogeneity tests should be performed before detailed modeling, hydrological and climatic analysis.

Combining COSMO-SkyMed data and machine learning for SWE monitoring in alpine areas

Emanuele Santi[1], Simone Pettinato[1], Simonetta Paloscia[1], Ludovica De Gregorio[2], Giovanni Cuozzo[2], Alexander Jacob[2], Claudia Notarnicola[2], Francesca Cigna[3], Tapete Deodato[3]

1 Institute of Applied Physics - National Research Council, Firenze, Italy
2 EURAC Research, Institute for Earth Observation, Bolzano, Italy
3 Italian Space Agency, Roma, Italy

Detailed and frequent mapping of the snow water equivalent (SWE) is required by several applications including hydrology, water management and climate changes. The capabilities offered by remote sensing techniques in estimating SWE at high spatial resolution and with frequent revisiting are therefore extremely attractive. Besides the well assessed capability of microwave radiometers, Synthetic Aperture Radar (SAR) sensors have also revealed some potential for operational SWE monitoring. Although the X-band (i.e. the highest frequency currently available on satellite SAR systems) is not the most suitable frequency for the retrieval of snow parameters, especially for shallow snow covers, past research on dry snow demonstrated that SWE values greater than 100-150 mm can be retrieved at X-band too, by using appropriate algorithms and models. Moreover, the new generation of X-band SAR satellites, offered significant improvements in terms of revisiting time and spatial resolution, which are crucial features for operational monitoring applications. This is particularly true for the Italian Space Agency (ASI)'s COSMO-SkyMed (CSK) mission that, thanks to its 4-satellite constellation, allows frequent revisiting of the target areas. This work aims at exploiting the information derived from CSK images acquired in StripMap HIMAGE mode at 3 m ground resolution, together with in-situ measurements for SWE retrieval in the entire province of South Tyrol (~7,400 km²), in north-eastern Italy. The SWE data considered as ground truth have been derived from manual snow profiles performed during the field campaigns by the operators and provided by the Hydrographic Office of the Autonomous Province of Bolzano. From the available dataset, 45 SWE values have been selected in correspondence to the CSK acquisitions in dry snow conditions. Data refer to the winter months of January and February of three years, from 2013 to 2015. The CSK X-band backscattering coefficients were compared with the in-situ SWE data to evaluate the sensitivity of microwave measurements to the target parameter. For interpreting the scattering mechanisms and assessing the obtained relationships, the experimental data have been also compared with model simulations based on the Dense Media Radiative Transfer theory in the Quasi-Crystalline Approximation (QCA) of Mie scattering of densely packed Sticky spheres (DMRT – QMS). Based on the results of the sensitivity analysis, the SWE retrieval has been attempted by using two machine learning techniques, namely Support Vector Regression (SVR) and Artificial Neural Networks. Training of both algorithms was based on experimental data and DMRT model simulations, by considering backscattering and incidence angle as inputs of the algorithm and SWE as output. After training, the algorithms were applied to the available CSK images to generate SWE maps of the entire area covered by the SAR acquisitions. The obtained results were encouraging, although more analysis and validation are needed to exploit the potential and assess the limits of CSK application to snow parameters retrieval. This work is carried out by EURAC, CNR/IFAC and ASI in the framework of the 2019-2021 project 'Development of algorithms for estimation and monitoring of hydrological parameters from satellite and drone', funded by ASI under grant agreement n.2018-37-HH.0.

Session 2: Snow cover dynamics- temporal and spatial variability

Multi-sensor wet snow mapping using wide-area radar backscatter composites

David Small[1], Gwendolyn Dasser[1], Christoph Rohner[1],

1 University of Zurich - Dept. of Geography, Zurich, Switzerland

The mapping of wet snow using time series of radar backscatter has traditionally been performed using single-track repeat comparisons. A dry cold reference backscatter image is first constructed by averaging a subset of acquisitions made under cold conditions. Later "candidate" images acquired with the same track are then compared against that reference, and a spatial map of regions where the backscatter dropped beyond a set threshold is generated. Retrievals based on this methodology unfortunately share the same heterogeneity in local geometric resolution of the single-track slant or ground range images used as input. Their local resolution is extremely poor on mountain fore-slopes due to foreshortening and layover. In contrast, on the back-slopes, an exquisitely high local resolution is available in both the input imagery and the retrievals made. If only that high local resolution could be made available across the whole region. In order to be able to provide a more evenly distributed quality of retrieval across a wide area, we propose a method whereby backscatter from multiple tracks is integrated into a single composite view of a large region. Wide-area composites are generated for defined time-steps, for the first time offering relatively consistent quality over large areas. A further advantage is that only one dry cold reference composite need be generated, rather than a different one for each relative orbit (track). In addition, the method is able to integrate data from multiple missions operated by different agencies. We demonstrate such integration with data from Sentinel-1 and Radarsat-2, and plan to add data from the three Radarsat Constellation Mission satellites once it becomes available.

Monitoring snow cover and snow phenology dynamics in global mountain areas by using MODIS images from 2000 to 2018

Claudia Notarnicola[1]

1 EURAC Research, Institute for Earth Observation, Bolzano, Italy

Mountain areas have raised a lot of attention in the past years, as they are considered sentinel of climate changes. Cryosphere is one of the most affected domains. Up to now, several studies have investigated snow cover changes at continental scale and there are several indications of snow cover decline over the Northern Hemisphere (Chen et al., 2015; Bormann et al., 2018), despite no study has analyzed snow behavior specifically in mountain areas at global level. In this context, this study investigates the changes in the main snow cover parameters (snow cover area, snow cover duration, snow onset, snow melt and snow line altitude) over global mountain areas from 2000 to 2018 (Notarnicola, 2020). In order to proper monitor the evolution of snow changes at global mountain areas and interlinkages with meteorological drivers (snowfall, and temperature), automatic procedures were developed based on MODIS imagery in global mountain areas over the period 2000-2018 by exploiting Google Earth Engine where the whole time series of MODIS is available at a global scale. MODIS snow cover products have the highest resolution available, 500 m, and with daily global acquisitions. Only recently with almost 20 years of data, these imageries have become useful to start assessing tends in snow cover and snow phenology. The results of the trend analysis carried with Man-Kendall statistics indicate that around 78% of the global mountain areas are undergoing a snow decline. More in details, snow cover duration has decreased up to 43 days, and a snow cover area up to 13%. Few areas show positive changes with snow cover duration increase up to 32 days, and snow cover area increase up to 11%. This latter behavior can be found during wintertime and in areas mainly located in Northern Hemisphere. Significant snow cover duration changes can be linked in 58% of the areas to both delayed snow onset, and advanced melt. Furthermore, snowmelt advance is going faster than snow onset delay in the analyzed time period. While snow cover, and the snow phenology parameters are quite variable at mid-elevations, from 4000 m upward only negative changes are detected. In the correlation with meteorological parameters, air temperature is found as the main driver for snow onset and melt, while a combined effect of air temperature and precipitation dominates the winter season.

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Changes in Andes snow cover from MODIS data, 2000–2016

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The Andes span a length of 7000 km and are important for sustaining regional water supplies. Snow variability across this region has not been studied in detail due to sparse and unevenly distributed instrumental climate data. We calculated snow persistence (SP) as the fraction of time with snow cover for each year between 2000 and 2016 from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensors (500 m, 8-day maximum snow cover extent). This analysis is conducted between 8 and 36 S due to high frequency of cloud (>30% of the time) south and north of this range. We ran Mann–Kendall and Theil–Sens analyses to identify areas with significant changes in SP and snowline (the line at lower elevation where SPD20 %). We evaluated how these trends relate to temperature and precipitation from Modern-Era Retrospective Analysis for Research and Applications-2 (MERRA2) and University of Delaware datasets and climate indices as El Niño–Southern Oscillation (ENSO), Southern Annular Mode (SAM), and Pacific Decadal Oscillation (PDO). Areas north of 29 S have limited snow cover, and few trends in snow persistence were detected. A large area (34,370 km^2) with persistent snow cover between 29 and 36 S experienced a significant loss of snow cover (2–5 fewer days of snow $year^{-1}$). Snow loss was more pronounced (62% of the area with significant trends) on the east side of the Andes. We also found a significant increase in the elevation of the snowline at 10–30 m $year^{-1}$ south of 29–30 S. Decreasing SP correlates with decreasing precipitation and increasing temperature, and the magnitudes of these correlations vary with latitude and elevation. ENSO climate indices better predicted SP conditions north of 31 S, whereas the SAM better predicted SP south of 31 S.

Snow cover analysis integrating satellite and terrestrial imageries over a decade

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The investigation on how the snow cover is evolving requires the availability of different data sources that can be integrated in order to enhance the definition of the snow cover evolution over long periods. Remotely sensed images offer nowadays long-time series concerning the spectral behaviour of the surface in mountainous areas. Different satellite products are available with different spatial and spectral resolutions and the normalization of such products can be obtained using terrestrial photography. This latter approach is becoming more and more frequent in Alpine environments and the development of information infrastructures and statistical tools are increasing the capability to reconstruct the snow cover distribution at different scales. This study investigates the support provided by terrestrial photography for the estimation of a site-specific threshold to discriminate the snow cover. The study sites are located in the Italian Alps where images taken over a ten-year period were analyzed using an automated snow-not-snow detection algorithm based on Spectral Similarity. The performance of this approach was initially investigated at a local scale comparing the results with different supervised methods on a training dataset, and subsequently through automated procedures on the entire dataset. The integration with satellite snow products was performed using a data cube infrastructure and we assessed the effectiveness of this approach a larger scale using a threshold derived by terrestrial photography. This analysis was performed using data over a decade.

A combined Terra/Aqua MODIS snow-cover product for the High Mountain Asia between 2002 and 2018

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Snow is a significant component of the ecosystem and water resources in the High Mountain Asia (HMA). Accurate, continuous and long-term snow monitoring is necessary for water resources management and economic development. In this study, we improved Moderate-resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua snow–cover for HMA by a multi-step approach. The primary purpose of this study was to reduce uncertainty in MODIS snow cover. For reducing underestimation mainly caused by cloud cover, we used seasonal, temporal, and spatial filters. For reducing overestimation caused by MODIS sensor, we combined MODIS Terra and Aqua snow-cover products considering snow only if a pixel is snow in both the products otherwise no snow, unlike some previous studies considering snow if any of the Terra or Aqua product is snow. Our methodology generates a new product, which removes a significant amount of uncertainty in raw MODIS 8-day composite product comprising 46% overestimation and 3.66% underestimation, mainly caused by sensor limitations and cloud cover, respectively. The results were validated using Landsat 8 data as ground truth, both for winter and summer at twenty well-distributed sites in the study area. Our validation results show that the adopted methodology improved accuracy on average by 10%, mainly reducing the snow overestimation. The final product covers the period from 2002 to 2018, as a combination of snow and glaciers created by merging RGI6.0 glacier boundaries separately debris-covered and debris-free to the final snow product.

Poster session: Snow remote sensing & experimental research

Snow cover evolution in the Swiss Alps using Earth Observation Data Cube

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In an alpine country like Switzerland snow cover represents a key feature involved in different processes such as natural water storage, alpine biota ecosystems, regional radiation balance and socioeconomic activities. Despite the high variability of snow cover evolution between years and sites, several studies revealed a decrease on snow cover extent, amount and duration over the past decades, particularly since the end of the 1980's. In a context of global warming, such trend will be strengthened in the near future, and its implications go far beyond mountain boundaries. The global coverage and regular repeatability of measurements offered by satellites images allow experts to map and monitor the vast temporal and spatial variability snow cover where in-situ measurements may be insufficient, expensive or dangerous. However, remote sensing techniques face various challenges in Alpine regions such as landscape heterogeneity and persistent cloud cover limiting the availability of cloud-free observations. Earth Observation Data Cubes (EODC), a new way of handling satellite data, represents a useful technology to tackle these challenges. This new system of storage allows to unlock the information of EO, often referred as Big Earth Data, and to produce large spatio-temporal and multi-sensor data in an analysis ready form [1]. Supported by the Swiss Federal Office for the Environment and jointly developed, implemented and operated by the United Nations Environment Programme /GRID-Geneva in partnership with the University of Geneva (UNIGE), the University of Zurich (UZH), and the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the Swiss Data Cube (SDC) is the second operational national EODC worldwide after Australia. Benefiting from medium to high-resolution optical imagery (Landsat-5, -7, -8 and Sentinel-2) and radar data (Sentinel-1) contained in the SDC, an automated snow detection algorithm, called Snow Observation from Space (SOfS), was developed to measure and monitor snow cover changes and trends over the Swiss Alps since the 1980's. Based on the NDSI approach, widely used to map snow cover in mountain regions, the SOfS algorithm uses a series of criteria and decision rules to identify snow in each pixel [2]. Spatial and temporal filtering techniques and multi-sensors analysis were used to reduce uncertainty and to infer information on cloudy pixels. The integration and combination of consistent and comparable data from different sensors provides new avenues and opportunities, increasing information density to minimize cloud contamination and to look further back in the past (CEOS). This study will allow Switzerland to benefit from long term data archives and readily products to support the 2030 Sustainable Development Goals by monitoring, measuring and managing the Swiss Alps environment.

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Standardized Snowpack Index (SSPI) in the Piave river basin

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The estimation of the available water resource in the Alps, as SWE, is of great interest for river managements purposes over spring and summer seasons. During the winter periods from 2010 to 2019, were frequent winter snow depths with less thickness than the average had. This situation highlighted the need to use appropriate drought indicators to estimate the water resource and the Snow Water Equivalent (SWE). The Standardized SnowPack Index (SSPI) is a probability indicator that evaluates a certain observed daily snow water equivalent value (SWE, kg m^{-2}) over certain time scales (10-30 years). For the Piave river catchment (Eastern Alps) the SSPI was experimentally calculated using the snow height data which came from automatic stations and snow density values measured directly in site and also mentioned in bibliography. Outcomes showed different winter characteristics. For example, in the last 10 years, the beginning of the melting snowpack started in the middle of March and not in April (15 days advance) showing very different values of SSPI.

Modelling spatio-temporal dynamics of snow depth and large herbivore's winter habitat selection

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Winter snowy conditions and the wildlife management strategies they encourage play a critical role in governing the spatial distribution of ungulates in temperate ecosystems. Snow depth severely restricts roe deer (Capreolus capreolus) distribution due to the limitations resulting from their small body mass (18-49 kg: Lister et al,1998) and short legs (50-60 cm: Holand et al. 1998). Due to these constraints, roe deer living in snowy areas adopt highly selective movement tactics. For instance, roe deer employ a partial migration strategy, with all individuals overwintering in ranges characterized by less extreme snow conditions, and some migrating in summer ranges which are usually at higher elevations. Recently, Brigth Bross et al (2019) examined how wintertime snow depth trends and increases in supplemental feeding practice affect habitat selection by roe deers in an alpine area, a region at the species' elevational range limit that is experiencing rapid climate change. This study has required a detailed estimation of snow cover spatio-temporal patterns. Therefore, GEOtop Hydrological Model Holand et al. 1998, Bortoli et al, (2019, in preparation, www.geotop.org) has been used and applied to the study case. GEOtop is a water- and energy-balance model that produces snow depth area maps from meteorological data, taking into account snow melting processes across the landscape. GEOtop executes simulations in continuum in small or relatively large mountain catchments. GEOtop deals with the effects of topography on the interaction between energy balance (evapotranspiration, heat transfer) and hydrological cycle (water, glacier and snow). 25-year long time series of weather data time collected in several stations through the study area are taken into account: in particular simulations has been run with observed data and both estimated data downscaled by regional climate model projections (COSMO-CLM, Rockel et al. 2008) in order to generate two further hypothetical 25-year long series corresponding to the two IPCC scenarios RCP 4.5 and RCP 8.5 . GEOtop has been validated with measurements collected in the sampling plots during field campaigns in 2012-2013 and 2013-2014 winters (Ossi et al,2015). Results show that snow occurrence at medium and low elevations , i.e the number of days with snow cover (snow depth > 5 cm) from December to April, in the decade 2006-2015 (latest year of the analysis) is more variable than in the past decade 1996-2005. Snow occurrence simulated with the climate projections confirm these outcomes. Furthermore, roe deers in presence of snow strongly try to select zones with canopy cover and avoid places with high snow depths. Therefore, interplay between selection of habitats in winters and changing spatio-temporal pattern of snow depth affected by increasing climate variability constitutes a challenge to future research in animal ecology and is a field of interest for applied snow hydrology.

Snow bias in EURO-CORDEX regional climate models and its dependence on topography mismatch and cold bias in the European Alps

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Snow is a key environmental parameter in mountains, and in this changing climate reductions in snow are expected. Traditionally, future estimates of snow are based on dedicated snow/hydrological models forced by climate projections, which, however, are computationally intensive and which decouple hydrology from climate forcing. Recently, regional climate models (RCM) have been used as an alternative, although snow is only an auxiliary parameter in RCMs and not as accurately represented as compared to dedicated snow models. Nonetheless, RCMs encompass the climate-hydrology feedbacks, cover large areas, and have become available in moderate horizontal resolutions (e.g. the EURO-CORDEX models are at approx. 12km). Here, we show that snow in RCMs is well represented given its moderate resolution and that most deficiencies are because of the mismatch in model topography and the cold bias in winter. For this, we compared the ERA-Interim driven EURO-CORDEX RCMs with a) snow cover from MODIS and temperature from E-OBS for the whole alpine area and the common period 2002-2008, and b) with station data for the province of Bolzano in Northern Italy for the period 1980-2008. The remaining differences between RCMs and biases to observations could then be attributed to the different snow modules in RCMs, since they were forced with the same climate (ERA-Interim).Consequently, the simple snow representation in RCMs might be enough for adequate large-scale assessments. As such, they provide a complementary view to the traditional approach of running dedicated snow models, which can provide a much more detailed view but only on a smaller area, typically catchments.This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 795310.

Estimating Multiscale Snow Cover Variability in the South of Western Siberia: SSSC Project framework

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Seasonal snow cover is a fundamental component of the global climate, energy and water cycles. In the southern regions of Siberia snow is an essential factor in runoff formation, sustainable agricultural production and ecosystem functioning. In recent decades snowpack duration has shown a tendency to decrease, as in many regions of the world. However, the average snow depth has been consistently increasing in open areas and decreasing in forested areas. Considering that snow cover is highly variable at multiple scales, it's becoming increasingly difficult to predict watershed response to environmental change.Within the framework of the South Siberian Snow Cover project (SSSC), we are planning to focus on (1) estimating variability of snow cover at multiple scales, (2) comparing the features of snow accumulation in different landscapes (from dry steppe to low mountains), (3) collecting data of the main snow properties (depth, density and SWE), which will be available for further studies. The project will be implemented jointly by Lomonosov Moscow State University and the Institute for Water and Environmental Problems SB RAS in 2019 – 2022.The study area located in the Altai region, which is a large agricultural region with high population density in the South of Western Siberia. This territory is extremely diverse, there are areas both suffering from desertification and areas with high flood risk. Within the framework of the SSSC project, observations will be carried out in three catchments: Kuchuk (steppe), Kasmala (forest-steppe), Mayma (low mountains). In each catchment we are planning to use a stratified nested sampling design. The watershed will be stratified into several strata by topography, vegetation (land cover) and elevation (for the mountain catchment). Within each strata 60 snow depths and 12 snow densities will be measured along two perpendicular transects (60x60 m plots). Observations will be carried out once a month during the winter (November-March) at 4-5 key plots in each catchment. During the period of maximum snow accumulation (at the beginning of March), extended snow surveys will be conducted on all plots (30-40 plots per catchment).One of the specific objectives of the SSSC project is the integration of hydrological and landscape ecological methods in snow science. We are planning to assess the isotopic composition of snow ($\delta^{18}O$, δD) which is widely used as a tracer of internal fluxes. At some plots depth of soil freezing will be measured, which is also one of the most significant parameters of winter ecosystem functioning. Besides, it is planned to explore snow distribution depending on the landscape structure parameters calculated using landscape indices.The main potential results that we are planning plan to achieve are SWE distribution models, as well as the comparative analysis of the snow parameters variability at multiple scales (plot, catchment, between catchments). We suppose it necessary to make the observational data available to a wide range of researchers, taking into account that not so many studies dedicated to Siberian snow cover have been published.

Hom4Snow: Homogenization of snow measurements for robust socio-economic Snow climate indicators in the Alps

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The presence or absence of snow has a profound impact on the society, for example in the strong tourism-dependent areas of the Alps. Profound information on the history, present and future of snow has a high value for alpine countries like Switzerland and Austria. The project "Hom4Snow" by the SLF, University of Graz, MeteoSwiss and ZAMG tries develop innovativ methods for homogenization of snow series and increase the number of quality-proven longterm snow series in Austria and Switzerland.Observations are influenced by non-climatic inhomogeneities, which range from changes in either the location, observers, individual measurement practices to changes in the measurement technology itself. These factors are highly likely to occur in longterm datasets and are affecting both the climatology itself but derived products which are used by research, stakeholders, decision makers and other users. To avoid influences on results, unfavourable or even wrong conclusions, it is therefore important to adress these issues in an early stage of the research process. Homogenized longterm-datasets with a high temporal resolution are clearly demanded, either as a base for further research or derived products. They are being used for validating models, detecting spatial and temporal patterns, trends or changes in the dynamics of a system. Also, the increasing demand for gridded datasets requires longterm quality-proven data as a foundation. It is important to give enough attention to the improvement and correction of observation-datasets. Most of the existing tools and algorithms that are being used for homogenization have been developed for air temperature and precipitation, whereas their application to snow depth measurements has only been rarely attempted. Until now, there have only been smaller efforts to develop methods and tools for snow series. The Hom4Snow-Project wants to break new ground by developing innovative methods for the homogenization of longterm snow observations as well as to demonstrate the impact of adjustments on climatologies and trends. We want to adjust existing homogenization methods to the specifics of snow series with break detection methods, correction and gap filling methods as well as to provide a benchmark for snow depth and new snow height time series homogenization using parallel measurements, homogenization method as well as simple snow modelling. As a basis to develop and apply adjustments on a daily basis, we are using longterm measurement series from the Swiss-Austrian domain for the two parameters which are measured most frequently: Snow depth (HS) and new snow height (HN).The results will help to quantify and understand the impact of non-climatic factors on snow observations, increase the number of available longterm high quality measurement series and provide more insight in the snow climatology of the Swiss and Austrian Alps. We want to show first results of the homogenization efforts based on the Austrian dataset from ZAMG and the Austrian Hydrographic Central Office, which range from 1895 to 2018.

Monitoring the snowpack internal stress by lineament domain analysis

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Lineament domains on the Earth surface revealed a good tool to infer the crustal stress field responsible for the tectonic deformation. Recent works highlighted the tectonic and geodynamic setting of icy satellites in the Solar System (e.g. Ganymede, Enceladus) by the quantitative analysis of the linear pattern developed on their surfaces. The same methodology was successfully applied also to study the state of brittle deformation of the East Antarctic Ice Sheet and of the Mars polar ice caps.The common finding of these works is that ice surface linear patterns cluster in azimuthal family set, called domains. The main lineament domain is systematically parallel to the horizontal component of the maximum stress. In this way lineament domains indicate the stress trajectories within the ice whose uppermost levels are characterized by swarm of crevasses and fractures.Inferring the stress field within the snow cover is of utmost importance to monitor its state of internal deformation as well as to forecast avalanches.Automatic lineament detection techniques have been developing for the last decades to identify alignments from satellite images. Thanks to the increasingly improved computation capabilities of the present-day computers and the availability of near real-time satellite images with spatial resolution ranging from 10^2 m (e.g. Modis) to 10 m (e.g. Landsat 8, Sentinel-2), the application of automatic lineament domains analyses on the snow cover represent a promising tool to monitor snowpack internal strain and its evolution through time. Approaching a slab avalanche event shear and extensional fractures develop in the snowpack and on the snow surfaces it is possible to recognize their spatial organization resulting from the internal snow stress trajectories.In the present contribution we present the preliminary results of the application of lineament domain analyses on the snow cover in regions affected by slab avalanches. Both satellite (Landsat-8 and Sentinel-2) and webcam images acquired prior and after the slab avalanche event were analyzed in order to identify the signature on the snow surface of the evolving, increasing strain within the snowpack that precede the avalanche event.

Theia Snow collection: high-resolution operational snow cover maps from Sentinel-2 and Landsat-8 data

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The Theia Snow collection routinely provides high-resolution maps of the snow-covered area from Sentinel-2 and Landsat-8 observations. The collection covers selected areas worldwide, including the main mountain regions in western Europe (e.g. Alps, Pyrenees) and the High Atlas in Morocco. The evaluation of Sentinel-2 snow products using in situ snow depth measurements, higher-resolution snow maps and visual control suggest that the snow is accurately detected in the Theia Snow collection outside forest areas and that the snow detection is more accurate than the Sen2Cor outputs (ESA level 2 product). The high revisit frequency of these snow maps enables to generate gap-free maps of the snow cover duration, to correct biases in snowpack models or to retrieve wet snow area in combination with Sentinel-1.

GNSS-based monitoring of snow water equivalent and snow liquid water content in different regions and altitudes and potential (snow) hydrological applications

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For various (snow)hydrological applications like water availability, hydropower generation and flood forecasts, information on snow water equivalent (SWE) and further snow cover properties is essential. Since a few decades, the use of GNSS (Global Navigation Satellite System) signals for the derivation of snow cover properties is increasing. For several years and during the ESA business applications demonstration project SnowSense (2015-2019), we developed a nondestructive approach based on GNSS signals to derive snow water equivalent (SWE), snow height (HS), and snow liquid water content (LWC) simultaneously using one sensor setup only. One static GNSS antenna of the sensor setup was placed on the ground below the snowpack and the other one on a pole above the snowpack, serving as a reference. Before the first snowfall, the baseline between the two antennas was determined with millimetre accuracy using Real Time Kinematic (RTK) positioning. By using a double differences approach between receivers and satellites, clock offsets and phase biases were eliminated and atmospheric errors were mitigated. As soon as snow accumulated on top of the ground antenna, the GNSS signals were delayed, refracted and attenuated compared to the signals, which travelled by the speed of light in air. Thereof, we derived the snow cover properties SWE, HS and LWC considering the varying dielectric properties of dry and wet snow. So far, this approach was tested and validated with reference measurements at the high-alpine site Weissfluhjoch, Switzerland, and at the subarctic site Forêt Montmorency, Quebec, Canada. Within the project SnowSense, such in situ GNSS snow measurement stations were further developed to target commercialization and were already installed at several locations in Canada, Switzerland and Germany. Since the winter season 2018/19 for example, we installed four sensors setups along a steep elevation gradient (820 m, 1185 m, 1510 m, and 2540 m asl.) within only a few kilometres in Eastern Switzerland. Thus, we aim to study and improve the performance of our GNSS approach facing more frequent melt-freeze cycles, which might lead to faster snow aging and different snow densities. Further, we combined the in situ GNSS measurements with a hydrological model and remote sensing products to generate spatially distributed SWE and melt-onset maps as well as continuously assessed runoff information, as e.g. over the entire island of Newfoundland, Canada. Results and potential application from different regions and altitudes will be presented.

Evaluating the trends of the Degree-Day Factors in the high-altitude regions

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Snow and glaciers are vital fresh water resources because they store winter precipitation and act as a large reservoir to provide water when it needed the most i.e. during spring and summer. In the recent decade, most of the results from the hydrological models show that the climate change will adversely affect the patterns of snow and glacier melt from the high mountainous regions around the world. In this backdrop it is critical to know more about the melting processes as well as factors driving it.Temperature-Index (TI) models have proved to be very useful when it comes to snow and ice melt runoff modelling in large catchments for two reasons. 1) They use temperature as an index variable to address the complex energy process, 2) It is a more empirical approach which can be very helpful to cater the data paucity in the high mountainous areas. TI models use the Degree-Day Factor (DDF) as a 'key' parameter which transforms one degree-day [°C.day-1] into daily melt depth [cm.day-1]. Literature enlightens that the DDF is not a constant parameter but it changes with the ripening of the snowpack.In the present research setting snow measurement datasets from three different altitudes in Japan (Enshurin 173m a.s.l.), Germany (Brunnenkopfhütte 1602m a.s.l.), and Pakistan (Deosai 4149m a.s.l.) has been collected and evaluated for the estimation of the DDFs. Initial findings show that the DDFs vary from 0.3 to 6.8 mm°C-1 day-1 in the German Alps during the snowmelt season over the measurement period. While DDFs range from 0.2 to 7.9 mm°C-1 day-1 in the Yamagata forest (Japan) where the snowfall can be =4m per year. The range is fairly wide in the Himalayas (Deosai) where the DDFs might increase to =10 mm°C-1 day-1 during the snowmelt season. In general, the DDFs show an increasing trend during the snowmelt season at different elevations, which not only demonstrates the altitude influence on the variability of the DDFs but also links to changing snow densities. Latter suggests that the DDFs should not be taken as constant because it changes with the location and needs to be estimated for different regions.

Keywords: Degree-Day Factor, Temperature-Index, Snow and Glacier, Modelling

A seasonal field campaign on the Hochjochferner glacier (South Tyrol) exploiting ablation stakes and the Terrestrial Laser Scanner. Challenges, benefits and comparison with modelling

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Hochjochferner is a glacier placed in the Eastern Alps, along the boundary between South Tyrol region and Austria. It ranges between 2800m and 3200m with an area of about 1 km^2. In this work are presented the results of the field campaign performed over the melting season May 2018 – October 2018 as well as a comparison with a distributed, extended temperature-index model (termed TOPMELT) implemented to estimate the ice melting spatial distribution.The field campaign involved two different types of measurements: a set of four ablation stakes installed at different elevations and a scanning survey by means of a Terrestrial Laser Scanner (TLS). The spatial ice melting pattern was reconstructed through an interpolation of two scans taken at different locations across the glacier while the ablation stake records were used to validate such TLS-based ice melting map.On the other hand, TOPMELT simulates the ice melt rate taking into account the clear sky direct solar radiation, the albedo and the air temperature. Temperature is assumed uniform in space with a linear lapse rate. TOPMELT was manually calibrated using ice melt observations recorded at the stakes and a comparison with TLS-derived ice melt map was performed. The results showed a general good agreement, proving the consistency of the implemented model and the potential of TLS to integrate common field measurements. However, several issues arose during the use of TLS, which hampered an optimal data acquisition. Despite these operational issues, TLS represents an appealing source of information since it allows the reconstruction of the spatial field of the glacier surface variations, thus providing a valuable dataset to calibrate and/or validate distributed models as well as characterize local glacier dynamics.

Session 3: Remote Sensing of Snow Properties

Enabling the next generation of water management with the Airborne Snow Observatory

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Operational runoff forecasting and water management in snowmelt-dominated watersheds commonly rely on index measurements of snow accumulation and melt or extrapolations from a small number of point locations or geographically-limited manual surveys. These data sources cannot adequately characterize the spatial variation of snow depth and snow water equivalent (SWE) – the primary determinant of snowmelt runoff magnitude and timing. The Airborne Snow Observatory uses an airborne laser scanning system, imaging spectrometer, and distributed modeling to map a time series of snow depth and SWE across full watersheds at high spatial resolution, providing an unprecedented snowpack monitoring capability and enabling a new operational paradigm. Beginning in 2013, the ASO has mapped snow depth and SWE, and provided low-latency snow depth and SWE maps to water management partners. These products enable more accurate runoff simulation and optimal reservoir management, consistently across normal years as well as years with unusual snow conditions. Concurrent development of a data assimilation, process-based snowpack modeling system allows regular monitoring of basin snow depth and water equivalent distributions throughout the duration of the snow season. This presentation will cover the development of the ASO system, highlight results, and discuss future plans for widespread implementation of this new application of multi-temporal laser mapping in operational water management.

Multi-platform, multi-sensor snow surface properties for energy balance and model validation

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Snow cover, snow albedo, and the impact of dust are important properties used to estimate snow water equivalent (SWE) and snowmelt. Near-real-time observations from satellites can be used to guide forecasts and historical records can be used to refine forecasting methods as well as improve our understanding of the cryosphere and interactions with the biosphere. Multiple platforms and sensors exist but the tradeoff between spatial and temporal resolution of available satellite data for estimating these snow surface properties remains a challenge. Daily observations of snow cover and snow albedo are available from MODIS and VIIRS at a resolution of 500 m and 1 km respectively, but snow properties vary much finer scale. Finer scale observations at 30 m from satellites such as Landsat that have been used for validation and calibration of MODIS and VIIRS algorithms are available but only at 16-day intervals. At 10 m spatial resolution, the Sentinel-2 satellites (a+b) have more frequent observations (10-day repeat for 1 satellite, 5-day repeat for 2) and harmonized Landsat and Sentinel-2 are nearly frequent enough to track snow accumulation and melt. However, currently no sensor at such a fine spatial resolution images Earth's whole terrestrial surface daily. We use a physically based spectral mixture analysis and spectral differencing approaches for mapping snow cover, snow albedo, and the impact of dust with surface reflectance inputs from VIIRS, MODIS, Landsat, and Sentinel. We share project examples from NASA, NOAA, and the California Department of Fish and Wildlife projects showing the utility of the data. For example, we fuse these multi-sensor data using random forests and find fused data exhibits good skill in cross-validation experiments. We assess the snow cover mapping with data from the Airborne Snow Observatory and commercial data from Digital Globe and Planet. Data are assimilated into the NOAA National Water Model, used for validation in the NOAA GFDL model, and drive melt in the Army Corp of Engineer's HEC-HMS and model. These physically-based snow property retrievals are critical in global energy budgets and to validate global and regional models.

Monitoring snow properties and snowmelt using thermal inertia

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Alpine catchments represent a fundamental reservoir of fresh water at mid-latitude. Remote sensing offers the opportunity to estimate snow properties in the optical, thermal and microwave domains. In particular, the possibility to estimate snow density from remote sensing is relevant and still represents a great challenge for the remote sensing scientific community. Since changes of snow density and liquid water content occur continuously in the snowpack, spatial and temporal patterns of optical and thermal data can give information about snowmelt processes. The main goal of this study is to evaluate if snow thermal inertia can be an indicator of snowmelt processes and to evaluate its relationship with snow variables, with particular attention to snow density. We used data from two sites for analyzing the temporal and spatial dynamics of snow apparent thermal inertia (APs) as a possible indicator of snowmelt processes. Data collected from AWS at the Torgnon site were analyzed during different hydrologic years (2012-2017) and snow modelling was used to estimated snow variables related to snow melt and to compare them with thermal inertia. A field campaign was also conducted in Val Formazza valley to test the relation between thermal inertia and snow density using Landsat-8 optical and thermal satellite data. In summary, results showed that snow dynamics and snowmelt processes can be monitored by observing APs variations. In particular, during the accumulation phase APs features low values. Then during the warming and ripening phases of the snowmelt a steady increase was detected and finally, during the output phase APs showed high values. Using Crocus simulations, field data, satellite images and AWS data, a regression model between snow density and APs have been identified. This could be used to estimate snow density from albedo and surface temperature, opening new perspectives for monitoring cryosphere from remote sensing. This study is a first attempt in exploiting thermal inertia for monitoring snow dynamics, and it may open new perspectives for early detection of snowmelt processes and snow parameters from remote sensing observations

Development of a novel approach for snowmelt monitoring in alpine areas by using multi-temporal and multi-sensor remote sensing imagery

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Snow accumulation and melt are crucial for the hydrological cycle strongly contributing to runoff, groundwater storage, flooding, wet-snow avalanches and contaminant release. Monitoring of snowmelt timing is challenging, given the scarceness of in-situ sensors. Hydrological models represent a valuable tool, but with intrinsic limitations due to the usage of simplified assumptions and the scarceness of input meteorological data. Remote sensing has shown to be a valuable tool for snow monitoring, providing spatially distributed information in remote and difficult to access areas. In particular, the recent launch of the Copernicus Sentinel satellite missions has opened new opportunities due to the systematic collection of high spatial resolution images with high acquisition frequency. However, the state-of-the-art methods do not properly exploit this large amount of heterogenous information. Hence, we aim at developing novel approaches being able to exploit the rich multi-temporal and multi-source data to monitor the snowmelt status. This is achieved by exploiting the multisensory information separately first and by developing data fusion techniques in order to improve the snowmelt retrieval. We first present a physically-based approach that exploits Synthetic Aperture Radar (SAR) time-series for snowmelt retrieval. This is achieved by observing the relationship between the presence of liquid water content inside the snowpack and the backscattering behavior at C-band (Sentinel-1) [Marin et al., 2019]. Secondly, we investigate changes in snow cover fraction (SCF) by merging low-resolution and high-resolution data. SCF is usually obtained by performing a linear regression given the normalized difference snow index (NDSI) [Salomonson and Appel, 2006]. We propose to improve the SCF retrieval from low resolution data by adaptively exploiting the high-resolution information. All the information obtained by SAR- and multi-spectral data can be fused for obtaining the correct timing of snowmelt on-set, with relevant implications on hydrological evaluations.

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A new era of remote sensing to constrain physically-based snow hydrologic modeling: Imaging spectroscopy of snow physical properties

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Atmospheric warming from greenhouse gases (GHG) is contributing to acceleration of snowmelt but its magnitude is uncertain due to our uncertainties in the controls on the dominant contributor to annual melt (90-95% of the net flux, absorbed sunlight, itself controlled by snow albedo. With increased solar absorption, warming and melt commence markedly earlier in the snow season. Despite this crucial role of albedo and solar radiation in snow and ice melt, sparse measurements have kept us from understanding the global distribution of controls on albedo, snow grain size (GS), and radiative forcing by light absorbing particles (e.g. dust, black carbon).While multispectral optical remote sensing has given us access to indications of the controls on snow albedo and in turn climatic feedbacks of the cryosphere in the Earth system, the uncertainties in these retrievals inhibit the proper quantification relative to GHG forcings. The accuracies required to understand the relative roles of changes in albedo and GHG radiative forcing in changing snow warming and melt require the spectral resolving capacity of the VSWIR imaging spectrometer, as annunciated in the need for the coming NASA Surface Biology and Geology mission concept [National Academies of Sciences, 2018].In this talk, I present the remote sensing retrievals and snowmelt modeling constraints we are applying to existing airborne and coming spaceborne imaging spectrometers. The algorithm suite, which derives from work with the NASA Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) program and implemented operationally with the Airborne Snow Observatory, explores the complete reflected spectrum in the visible through shortwave infrared wavelengths to quantitatively retrieve (i) snow spectral albedo, (ii) snow broadband albedo, (iii) snow effective grain size, (iv) radiative forcing by light absorbing particles, (v) snow liquid water content, and (vi) snow algae concentration. Through the NASA Earth Science US Participating Investigator program, I am creating the cryosphere component of the German Aerospace Center EnMAP imaging spectrometer mission, the EnMAP Cryosphere Collective (EMC2), and participate in defining the mission operations to facilitate the cryosphere science. This suite is also being used to define algorithms and science of the NASA SBG concept. In the coming decade, we will have many spaceborne imaging spectrometers that will allow a marked improvement in our understanding of the global distribution of snow hydrologic response to changes in GHG, albedo, and associated feedbacks.

Session 4: Remote Sensing of Snow Properties

Snow parameters estimation through new data fusion approaches involving a hydrological model and remote sensing products

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Monitoring the snow coverage and understanding the internal snowpack processes is crucial in mountainous areas for the role of snow as water reservoir in hydrological cycle. Traditional methods for snow properties retrieval are based on pointwise observations collected by operators or at nivometeorological automatic stations. However, both acquisition methods are limited in space and cannot provide information in remote areas. To overcome these limitations, a commonly used approach is the use of physically based models. Although extensively tested and validated in gauged areas, these models are still affected by uncertainties in spatially distributed applications, due, among other things, to their connection to meteorological data, which are pointwise observations and need to be spatialized to the regional scale. Remote sensing (RS) can make a valuable contribution, by providing information at higher spatial and temporal resolution. Nevertheless, remote sensing has some limitations. Snow detection with optical sensors in clouded or shadowed areas and under the canopy is a still open issue for scientific community. Moreover, optical sensors are not suitable to obtain volumetric information about snowpack and for this purpose microwave sensors are needed. In particular, the most commonly used methods for retrieving volumetric snow properties from the space rely on passive microwave sensors whose use is limited by the poor spatial resolution. Accordingly, the combined use of RS and physical models could be the suitable solution to overcome the cited limitations and exploit the strengths of both methods. The aim of this work is to develop new methods for improving the estimation of three cryospheric parameters by exploiting the physically based model AMUNDSEN, optical RS products and, as reference samples, the collected ground observations. In particular, the three parameters addressed in this study are: the snow cover area (SCA), the snow water equivalent (SWE) and the glaciers mass balance (GMB), over the study area including the Tyrol, the South Tyrol and the Trentino regions. Differently from standards application where RS is used for model calibration of data assimilation, the proposed fusion scheme is based on machine learning techniques, always involving the final products of both RS and model outcomes. Results derived from developed methods are promising for all three parameters, by showing a general performances improvement: for SCA, the average agreement between the fused product and the reference ground data is of 96%, compared to 90% of the RS product and 92% of the AMUNDSEN simulation; regarding the SWE, the proposed method decreases, with respect to the AMUNDSEN simulations, the RMSE and the MAE with ground data, on average, from 154 to 75 mm and from 99 to 45 mm, respectively. Finally, the significant improvement obtained on the annual GMB estimation with respect to the AMUNDSEN model in terms of RMSE (i.e., 195mm vs 475mm), demonstrates the importance of integrating the RS data and the in-situ measurements with the physical model.

Monitoring snow water in mountain areas of Northern Sweden: performance evaluation of satellite/modelled snow products and exploration of microwave brightness temperature for characterizing snow accumulation/ablation

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All over the world, snow-melt from mountain areas provide water supplies to billions of people. A better understanding of the volume and distribution of snowpacks provides key inputs for planning purposes, such as for the hydropower industry. Due to the inaccessibility, complex topography and a lack of sufficient ground data in remote mountain areas, the characterization of snow water equivalent (SWE) distribution in mountainous terrain remains one of the most challenging topics in snow hydrology. Focused on the Överuman catchment in Northern Sweden, the goal of this work is to (1) investigate the performances of best available satellite and modelled SWE products in this region via comparisons against the ground measurements and to (2) explore the time-series passive microwave brightness temperature data for characterizing snow accumulation/ablation during the snow season, aiming to develop an improved regional product. The main data used include the 5 km resolution satellite SWE product generated by Finnish Meteorological Institute (available from Copernicus Global Land service), 1 km resolution SWE data generated by the SeNorge model (available from Norwegian Water Resources and Energy Directorate), 0.1 degree resolution Advanced Microwave Scanning Radiometer 2 (AMSR2) brightness temperature data (available from Japan Aerospace Exploration Agency), and snow depth/SWE field measurements. In general, current SWE products have low quality for applications in the study area. Significant differences were observed for both satellite and modelled data against the ground measurements, with general underestimation for the satellite product and overestimation for the SeNorge product in most sites. Preliminary results show that AMSR2 brightness temperature has great potentials for characterizing the seasonal snow evolution process; however, developing a reliable SWE retrieval algorithm requires more in-depth exploration of other relevant factors which might impact satellite signal and snowpack interaction. Further efforts are highly needed from both remote sensing and hydrological modelling community to improve the accuracy of snow water estimation, and thus provide more accurate inputs to the hydropower industry for regulating the water level of reservoirs.

Snow depth variability in the Northern Hemisphere mountains observed from space

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Accurate snow depth observations are critical to assess water resources. More than a billion people rely on water from snow, most of which originates in the Northern Hemisphere mountain ranges. Yet, remote sensing observations of mountain snow depth are still lacking at the large scale. Here, we show the ability of Sentinel-1 to map snow depth in the Northern Hemisphere mountains at 1 km² resolution using an empirical change detection approach. An evaluation with measurements from ~4000 sites and reanalysis data demonstrates that the Sentinel-1 retrievals capture the spatial variability between and within mountain ranges, as well as their inter-annual differences. This is showcased with the contrasting snow depths between 2017 and 2018 in the US Sierra Nevada and European Alps. With Sentinel-1 continuity ensured until 2030 and likely beyond, these findings lay a foundation for quantifying the long-term vulnerability of mountain snow-water resources to climate change.

Suitable digital elevation model spatial resolutions for structure-from-motion snow depth mapping in mountain areas

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Structure-from-motion (SFM) snow depth mapping with drones is capable of producing highly accurate local snow distribution observations in very fine detail. Typically to ensure the highest quality data, both the SFM surveys of the snow-covered and snow-free terrain are designed to obtain similarly high spatial resolution digital elevation models (DEMs). However, due to the dynamic nature of snow cover and potentially narrow window of time that allows for optimal field site conditions to perform drone surveys, surveying the snow-covered terrain to obtain very high spatial resolutions (≤ 10 cm) poses a challenge to cover larger scale areas. Furthermore, such finely detailed snow-covered DEMs may not always be necessary to obtain highly accurate depth observations. In this study, we investigate the effect of the snow-covered and snow-free DEM spatial resolutions on the accuracy of SFM snow depth mapping for a periglacial field site located in the southern French Alps. We compute snow depths by resampling DEM resolutions from 5 cm to 10 m. Three scenarios were tested: (1) only the snow-covered DEM resolution was coarsened, (2) only the snow-free DEM resolution was coarsened and (3) both DEM resolutions were coarsened. The snow depth accuracies of the DEM resolutions from drone surveys taken at flying heights of 60, 80 and 100 m above ground level were also compared. Accuracies were determined by comparing the computed snow depths to 80 snow probed measurements with point locations mapped using PPK-GNSS surveying (positional accuracies ≤2 cm at 1σ). Overall, the results show that snow depth accuracy was more sensitive to the spatial resolution of the snow-free DEM than the snow-covered DEM. The accuracy (root mean squared error; RMSE) related to the spatial resolution of the snow-covered DEM only decreased for resolutions coarser than 5 m. Additionally, we observed that when the spatial resolutions of the snow-free and snow-covered DEM are both coarsened, the accuracy (RMSE) decreases by 5 cm for every 1 m coarsening of the spatial resolution.

Snow Hydrology and Modelling

Keynote lecture

"Snow hydrological modelling and observations for the hydropower industry in the deregulated Nordic energy market"

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More fossil free energy production is urgently needed to limit global warming within an acceptable regime. Currently, generation of electric energy is one of the main sources for greenhouse gas emissions contributing to climate change worldwide. This picture may be changing, at least in the European Union, where the fraction of renewable energy is projected to increase from 30 to 50% within the next ten years, mainly due to the rapid growth of solar and wind power generation. However, this sort of power generation requires a balancing source due to their high fluctuations in production in response in variations in meteorological conditions. Now, hydropower is the only fossil free energy source that can act as such a balancing component, provided it is utilized well. For optimizing the production, detailed knowledge of hydrological conditions is fundamental. However, the information needed to optimize the production varies between individual power plants and sets important requirements on snow and hydrological modelling. In this presentation, the different information needs for a representative selections of power plants will be given and related to recent developments and challenges within snow hydrology.

Session 1: Progress in simulating snow processes and model evaluation

Snow management with physically based snowpack models for Alpine ski resorts: the PROSNOW project

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Snow on the ground is an important resource for mountain regions to sustain river flow, to provide freshwater input to ecosystems and to support winter tourism. The level of activity, employment, turnover and profit of hundreds of ski resorts in the European Alps primarily depends on meteorological conditions, in particular natural snowfall, but nowadays also conditions favorable for technical snowmaking. In order to mitigate the impact of the large inter-annual variability in natural snow, and more recently as adaptation to the effects of climate change, ski resort managers have massively improved their snow management. Nonetheless, there is still a significant potential to increase the efficiency of snow production by improving the anticipation capabilities at all time scales, spanning from “weather forecast” (up to 5 days typically) to “seasonal prediction” at longer scales (up to several months). In this context the PROSNOW project, financed by the European Union, addresses this potential by building a demonstrator of a snow management system based on weather and climate forecasts from a few days to several months ahead. PROSNOW applies state-of-the-art knowledge relevant to the predictability of atmospheric and snow conditions. In detail, the snowpack models AMUNDSEN (Strasser, 2008), Crocus (Vionnet et al., 2012), and SNOWPACK/Alpine3D (Bartelt and Lehning, 2002; Lehning et al., 2006) are applied to compute the expected snowpack conditions. These models comprise sophisticated snow management modules configured to work over 9 representative ski resorts located in the European Alps i.e., France, Switzerland, Germany, Austria and Italy. Within a demonstrator, snow height and SWE will be provided along with the meteorological variables at numerous predefined ski resort reference units (SRUs). The uncertainty of the predictions is simultaneously displayed on the basis of ensemble forecasts. The aim of this work is to present an overview on how the three snowpack models have been developed to simulate the natural snow conditions as well as the influence of snowmaking. This includes the possibility to choose different snow making settings and grooming in response to the ski resorts management practices. The first results of the application of the models in operational conditions will be presented together with a tailored validation using satellite images coming from the Copernicus Sentinel-2 mission.

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Process-based simulation of snow cover evolution in ski resorts with AMUNDSEN: first results from the PROSNOW project

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Snow management, i.e., snowmaking and grooming, is an integral part of modern ski resort operation. While the current snow cover distribution on the slopes is often well known thanks to the usage of advanced monitoring techniques, estimates about its future evolution are usually lacking. Management-enabled numerical snowpack models driven by meteorological forecasts can help to fill this gap. In the frame of the H2020 project PROSNOW such software tools are developed to be run on an operational basis with the aim to optimize snow management as well as the use of water and energy resources. As part of PROSNOW, model simulations for the ski resorts Seefeld and Obergurgl (both Austria) as well as Colfosco and San Vigilio (both Italy) are performed with the physically based snow model AMUNDSEN. In its particular snow management module, both socioeconomic and physical factors are considered, the former concerning the decision when, where and how much snow should be produced, and the latter considering the snowmaking conditions, i.e., how much snow can be produced in the current ambient conditions (in terms of temperature and humidity) and the given ski resort infrastructure (number and efficiency of snow guns, water availability, etc.). In our contribution we show how snowmaking and grooming practices are implemented in the AMUNDSEN model, how they can be adapted to individual ski resorts, and how we account for different potential snow management strategies in operational simulations. We present model results obtained using historical meteorological observations and hindcast simulations and validate them against Sentinel-2 snow cover maps as well as in-situ data obtained from the ski resorts such as snow depth measurements on the slopes and water consumption recordings.

Sensitivity of snow models to the accuracy of meteorological forcings in mountain environment

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Snow models are a powerful tool to simulate the past and current variability of snowpack characteristics and to estimate future snow changes at spatial scales useful for practical applications. In the former case snow models are forced by meteorological data from in-situ stations, from interpolation of surface station measurements, or reanalyses while in the latter case snow models are forced by meteorological time series provided by climate models run under different future scenarios. Currently available snow models are characterized by different degrees of complexity. Multi-layer, physically-based snow models are typically used to reconstruct the vertical structure of the snowpack with a high level of detail and high accuracy, while empirical snow models are employed when a coarse estimate of snow depth is sufficient. Among the major challenges for cryospheric modeling research are i) the quantification of the snow model complexity needed to achieve accurate estimates of the snow depth and mass in the different modeling frameworks; ii) the assessment of how the accuracy of the meteorological variables used to force snow models affects the quality of the snow simulations. This aspect is crucial in high mountain environments, owing to the high spatial variability of meteorological parameters in complex topography. We address these two overarching questions by devising a modelling experiment which employs several physical and empirical snow models which are characterized by different degrees of complexity, namely SNOWPACK, GEOTOP, HTESSEL, UTOPIA, SMASH, S3M. We analyze the skills of the different models in reproducing the snowpack temporal evolution during five snow seasons, from 2012 to 2017, at the experimental site in Torgnon, 2160 m a.s.l., Western Italian Alps. The selected site is equipped with an OTT-Pluvio2 rain gauge which ensures more accurate estimates of winter solid precipitation with respect to standard devices. The model performances are compared in different cases: i) the “ideal” case, when high-frequency and accurate meteorological in-situ station data are available (from the observing systems installed at Torgnon), ii) the case when data are provided by gridded data sets derived by spatial and temporal interpolation of nearest surface station measurements, and iii) the case when forcing is provided by global reanalyses, such as ERA-Interim and the latest ECMWF product ERA5, at spatial resolutions of ~80 and ~30 km, respectively. The study provides information on how sensitive the snow models are to the accuracy of forcing data, exploring the feasibility of driving these models with coarser spatial and temporal resolution data sets, including interpolation of surface station measurements and reanalyses, the only data typically available in remote mountain areas. Based on our results obtained for the Torgnon site, we discuss the trade-offs between model complexity and model performances, with the perspective of employing the best performing models to simulate past and future condition of mountain snowpack at fine spatial scales.

Efficient multi-objective calibration and uncertainty analysis of distributed snow simulations in rugged alpine terrain

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In steep and complex mountainous terrain, robust simulations of snow accumulation and ablation are important in many applications, especially those related to hydrology and ecology. Whilst new opportunities exist to integrate high-resolution spatio-temporal observations in the estimation calibration of sophisticated, process-rich snow models, these remain to be fully exploited. Here, with a view towards improving representations of snow and ultimately meltwater dynamics in rugged topography, a novel approach to the calibration of a high-resolution energy balance-based snow model that additionally accounts for gravitational snow redistribution is presented. Several important but uncertain parameters are estimated using an efficient, gradient-based method with respect to two complementary types of snow observations – snow extent maps derived from Landsat 8 images, and snow water equivalent (SWE) time-series at two contrasting locations. When assessed on a per-pixel basis over 17 days that encompass practically the full range of possible snow cover conditions, snow patterns were reproduced with a mean accuracy of 85%. The spatial performance metrics obtained compare favorably with those previously reported, whilst the simulated temporal evolution of SWE at the stations was also satisfactory. Subsequent uncertainty and data worth analyses showed that: i) the propensity for model predictions to be erroneous was substantially reduced by the calibration process, ii) pre-calibration uncertainty was largely associated with two parameters that were introduced to modify the longwave component of the energy balance, but this uncertainty was greatly diminished by calibration, and iii) the lower elevation SWE time-series was particularly valuable despite the comparatively small number of observations at this site. Alongside a gridded snowmelt dataset, commensurate estimates of firn melt, ice melt, liquid precipitation, and potential evapotranspiration were also produced. Our study demonstrates the growing potential of combining observation technologies and state-of-the-art inverse approaches to both constrain and quantify the uncertainty associated with alpine snow dynamics simulations.

Snow water equivalents exclusively from snow heights and their day-to-day changes

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Many hydrological applications depend on good estimates of snow water equivalent (SWE). Modern snow models like CROCUS, SNOWPACK or SNTHERM resolve mass and energy exchanges within the ground-snow-atmosphere regime in a detailed way and also resemble the layered structure of seasonal snowpacks. They all model SWE sufficiently well. However, they all need meteorological input data like temperature or radiation measurements. Unfortunately, many long-term series of total snow heights H do not come along with these data, and parameterizing or downscaling them from other sources isn't straightforward either. Even markedly more simple models at least require temperature and precipitation measurements as inputs, or climatological means thereof. Consequently, no process-resolving snow model is applicable to derive SWE exclusively from H.
On the other side of the snow modeling spectrum, there are models that depend on correlations between bulk density and snow height, date, altitude and regional parameters, or on a mixture of these. Those "statistical" models very much rely on the strong, near-linear dependence between H and SWE. Depending on calibration focus, statistical models therefore naturally fail to model mean or peak SWE sufficiently well, because they simulate unrealistic peak SWE or implausible mass losses during melt-free pure-metamorphic compaction phases. In addition and as a consequence, the timing of peak SWE as well as the duration of heavy snow loads cannot be modelled well. As honestly stated in the literature, those statistical models are therefore not suitable to calculate SWE for individual days. There exists at least one other promising approach, which uses the evolution of daily snow heights via a correlation between H and bulk density. Unfortunately, this requires H – density training sets, thereby heavily limiting the use of this approach.
We present here a new possibility to model SWE only from day-to-day snow height changes. It is based on the semi-empirical model of Martinec and Rango (1991), which describes daily snow compaction as a time-dependent power function. The new model considers daily snow height changes (ΔH) as a proxy for the various processes altering bulk snow density and SWE. It further provides a way to deal with uncertainties in the H-measurements, takes into account increased, sudden compaction due to overburden snow, and – optionally – provides a way to handle rain on snow. The new approach bridges the gap between sophisticated process-resolving models, needing lots of meteorological input, and statistical models, which are "overregulated" by snow height. We present an error analysis for this new modelling-approach which is referred to as Δsnow.model.

Session 2: Progress in simulating snow processes and model evaluation

Validation of ERA-5 snow water equivalent reanalysis over the Upper Adige River Basin (Italy)

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Here we present a regional scale evaluation of precipitation, temperature and snow water equivalent ERA-5 reanalysis compared to a network of 88 rain gauges and 124 temperature gauges and simulation obtained from the TOPMELT snowpack model for the Upper Adige river basin, Italy (6923 km^2, altitude from 200 to 3900 m a.s.l). The assessment is carried out over the period from 2002 to 2018. TOPMELT provides a fully spatially distributed simulation of the snow water equivalent (with a spatial resolution of 250 m) by exploiting a statistical representation of the distribution of clear sky potential solar radiation. This is obtained by discretising the full spatial distribution of clear sky potential solar radiation into a number of radiation classes. The computation required to generate a spatially distributed water equivalent reduces to a single calculation for each radiation class. This turns into a potentially significant advantage when parameter sensitivity and uncertainty estimation procedures are carried out. TOPMELT was calibrated and validated over the study area by using local snow stations as well as MODIS and Sentinel-2 remote sensing observation of the snow-covered area. TOPMELT model parameter uncertainty was taken into account by using 1000 Monte Carlo simulations. 10 ERA-5 ensemble members were considered to provide an assessment of ERA-5 uncertainty. For the purpose of the comparison, we considered the ERA-5 median value (computed based on the ten ensembles) and the median and the 50% inter-quantile range of the TOPMELT simulations. Errors were characterized at daily time step by computing the relative bias (RB), Nash-Sutcliffe efficiency (NSE) between ERA-5 and reference median and the percentage of ERA-5 median falling in the 50% inter-quantile range (RF). Relative bias assessment shows that precipitation and SWE are generally overestimated, with precipitation ranging from 15% to 45% and SWE ranging from 6% to 96% cross the different grids covering the study area. NSE for snow water equivalent ranges between 0.44 and -0.92. RF ranges generally between 0.45 and 0.53. It is shown that errors in ERA-5 snow water equivalent over the study region are controlled by precipitation overestimation and temperature errors related to the distortion of topography due to the large-scale ERA-5 representation.

Monitoring and simulating snow accumulation on the lowest perennial ice field of the Alps

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The mass balance of very small glaciers and ice fields is often governed by anomalous snow accumulation, winter precipitation being multiplied by snow redistribution processes (gravitationally or wind-driven). In a case study, we analyse the relative contribution of snow accumulation governing the mass balance of the lowest perennial ice field of the Alps, the Ice Chapel, located at 870 m a.s.l. in the Berchtesgaden National Park (Germany) at the bottom of the 1800 m high Watzmann East face.
Terrestrial laser scan (TLS) measurements during the winter season 2017/2018 suggest that 92% of snow accumulation at the Ice Chapel surface was gained by snow avalanching, thus clearly governing the winter mass balance of the ice field with mean snow depths of 32 m at the end of the accumulation period. Avalanche deposition is amplified by preferential deposition of snowfall in the wind-sheltered rock face surrounding the ice field. These huge amounts of snow accumulation cannot be captured by models if applying traditional hydrological model systems and spatial interpolation methods that do not account for the respective lateral snow transport processes.
We used TLS measurements to test and validate different parameterizations of wind-driven and gravitational snow transport within the physically-based snow model AMUNDSEN. The model was implemented in different spatial discretizations ranging from 50 m to 10 m in horizontal spatial resolution. The results show that the model parameterizations generally enable to capture the measured total snow depth and its spatial distribution. However, the performance of the snow transport models strongly depends on initializing the correct main wind direction. A high spatial resolution of at least 10 m is required to simulate the precise locations of largest snow accumulation.

Multi-level spatiotemporal validation of hydroclimatological modeling results in mountain areas: method and data collection

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In a numerical simulation experiment, we introduce multilevel spatiotemporal validation as a systematic, independent, complete, and redundant validation procedure based on the observation scale of temporal and spatial support, spacing, and extent. The hydroclimatological model exemplarily applied is the distributed, physically based framework AMUNDSEN, set up for catchments in the Ötztal Alps (Austria) at a spatial resolution of 50 m and a temporal resolution of 1 h for the period 1997–2013. Our approach is demonstrated using a comprehensive set of eight independent validation sources: (i) mean areal precipitation derived by conserving mass in the closure of the water balance, (ii) time series of snow depth recordings at the plot scale, (iii–iv) multitemporal snow extent maps derived from Landsat and MODIS satellite data products, (v) the snow accumulation distribution derived from airborne laser scanning data, (vi) specific surface mass balances for three glaciers in the study area, (vii) spatially distributed glacier surface elevation changes for the entire area, and (viii) discharge recordings for several sub catchments. The results of our numerical experiment demonstrate the benefit of the new validation approach. The method can serve as guideline for systematically validating the coupled components in integrated snow-hydrological and glacio-hydrological models. To force and validate the simulations a comprehensive hydrometeorological and glaciological data set is employed, originating from a multitude of glaciological, meteorological, hydrological and laser scanning recordings taken at autonomous weather stations, discharge gauges, and a series of distributed (airborne and terrestrial) laser scans, complementing the satellite data used in our study. A permanent terrestrial laser scanner installed 2016 on “Im hintern Eis” (3244 m a.s.l.) to continuously observe almost the entire area of Hintereisferner is unique in its position. The data and research undertaken at the sites of investigation enable combined research of cryospheric, atmospheric and hydrological processes in complex terrain and ideally support the development of modelling studies like the one presented here. Our core site, the Rofental (1891–3772 m a.s.l.), is promoted in several international research initiatives, e.g. LTSER (Long-Term Socio-Ecological Research, https://www.lter-austria.at/rofental/) or INARCH (International Network for Alpine Research Catchment Hydrology, http://words.usask.ca/inarch). The original research data sets are provided to the scientific community according to the Creative Commons Attribution License by means of the PANGAEA repository (https://doi.org/10.1594/PANGAEA.876120).

Parameter uncertainty assessment for a conceptual hydrological model in a snow-dominated catchment combining streamflow records and MODIS snow cover maps

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Conceptual hydrological models describe the different hydrological processes through empirical relationships, driven by several, often non-physical, parameters. The estimation of such model parameters introduces significant uncertainty on the prediction of both streamflow and the other components of the hydrological balance. In this work, we propose a multi-objective parameter uncertainty analysis, combining streamflow records and MODIS-derived snow-covered area (SCA) images, based on the well-known GLUE procedure in order to quantify the predictive parametric uncertainty of streamflow, SCA and mean areal snow water equivalent. This procedure was tested at Passirio river catchment, a mountainous catchment ranging from 360 m to 3500 m with a contributing area of about 400 km^2 placed in the upper Adige river basin (South Tyrol, Italy). Firstly it was evaluated at the catchment scale and secondly it was applied in an upstream sub-catchment, to spatially validate the proposed approach. Conditioning the hydrological model with the multi-objective approach instead of using only streamflow data show that: both SCA and mean areal SWE predicted uncertainty bands reduce up to 30%; the streamflow uncertainty range shrinks up to 11% at the outlet section and up to 17% in the upstream sub-catchment. These results suggest that the presented procedure might be appealing for inferring uncertainty bounds of streamflow and snow-related predictive variables at different, perhaps poorly gauged, locations across the catchment.

SNOW4 - An Operational Model for Precipitation Supply Forecasts

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SNOW4 is a grid-based model for analysis and short-term forecasting of snow cover formation and depletion. The core of the model consists of a set of physical equations which describe the snow cover energy and mass balance. The energy balance module estimates the available melting heat based on radiation balances and heat fluxes between atmosphere, soil and snow cover. Depending on whether the melting heat is positive or negative, snow melts or liquid water freezes within the snow layer. Taking retention, aging and regeneration of snow into consideration, the model computes the evolution of the snow cover. The model computes hourly snow depth, snow cover water equivalents and precipitation supply from snow melt and rain falling into the snow layer. Gridded observations are used both to drive the model during an analysis cycle over the last 30 hours before the current forecast time and to define the initial state of the model for the subsequent forecast cycle. For this purpose, hourly measurements of air temperature, water vapour pressure, wind speed, global radiation and precipitation are interpolated to the model grid. For generating 3-day forecasts, SNOW4 is driven by operational hourly products of the ICON-EU weather forecast model. The size of a grid box is approximately 1 km^2; the model covers an area of 1250 km x 1050 km centered over Germany (including the entire catchment areas of all rivers in Germany except for the Danube – only the German part of the drainage basin is covered for this river). The internal model time step is 1 hour. Once a day, the agreement between model and regionalized snow cover data is assessed. If discrepancies exceed certain thresholds, the model is adjusted to the observations using weights. The model computation starts at 01 UTC, based on the most recent observations until 00 UTC and the 78-hour ICON-EU forecast of 18 UTC of the previous day in which the first 6 hours are removed. The simulations are updated every six hours. The model has been fully operational since winter 2010/11. A comprehensive evaluation focusing on water equivalent gave evidence for a good overall performance. SNOW4 products are mainly supplied to users involved in water management and flood protection. They are used as input data for flood warning and short-term hydrological forecasting systems. Outputs are available in several ways. Individual users receive model results for specific sub-areas of the model region tailored to their particular requirements (password-protected). Such SNOW4 products have so far been produced for the German Federal Institute of Hydrology (BfG), more than ten flood-forecasting authorities of the German Länder and a number of foreign authorities in Austria, the Netherlands and Poland. Analysis and forecast plots covering the entire model region enter WaWiS, the water management weather information system of DWD (closed user group). For the German territory, SNOW products are provided in ASCII format on the open data server of DWD. For the German territory, SNOW4 products are provided in ASCII format on the open data server of the DWD.

Poster session – Progress in simulating snow processes and model evaluation & Snow-Atmosphere Interface

The effects of forest cover on snow water equivalent-Results from the "5th SWE intercomparison"

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The role of forest stands in estimating the snow water equivalent (SWE) over large areas is mainly related to the physical barrier they create, which make both direct and indirect measurements more difficult, and to the influence they have on the properties of the snowpack.
The goal of the 5th SWE INTERCOMPARISON meeting, hold in Bolzano (BZ) on 18 and 19 March 2019, was to test a new survey scheme for field teams in order to improve the estimation of SWE in alpine environments, as well as to investigate the relationship between degree of forest cover and SWE. The work required a day of field surveys, with the aim of acquiring as much data as possible over a wide area. The survey scheme was designed based on the already available literature, according to which forest cover determines a reduction in snow height (HS) compared to a non-forest area under the same topographical conditions. The sampling sites were identified in the Ski Center Latemar area (BZ) using orthophotos, to include forest areas with different degree of cover and open field areas. In total, 79 sites were investigated, collecting 22 values of HS [cm], 1 value of snow density [kg m^{-3}] and 1 value of stand density [number of trees ha^{-1}] for each measurement site. Overall, the altitudinal range is between 1520 and 2490 m a.s.l., the stand density between 0 and 2546 trees ha^{-1} and the SWE between 4 and 386 mm. The collected data allow coupling 51 values of HS in the forest with as many values outside the forest and to calculate the relative delta HS (ΔHS = HSforest - HSopen field). In 43 cases this difference is negative, while in 8 cases it is positive (more snow in the forest compared to the open field). On average, the reduction of HS in the forest is 27%. In terms of SWE, the reduction is 34%, due to the fact that the snow density is on average lower in the forest (-14%) than in the open field. The second aspect analysed relates to the influence of the reduction effect caused by different forest stand densities. In order to investigate this factor, the sampling sites were classified into three macro-categories of stand density. The statistical tests show a significant difference between HS in open areas and in denser forest conditions, while the intermediate conditions of sparse and medium dense forests are not differentiated. The same applies for SWE.
In general, the adopted sampling design worked well for the intended purpose. By estimating the density of the forest in a qualitative way by class, it is possible to observe a reduction of HS, SWE and snow density in the densest forests, when compared to the open field sites. To better investigate the relationship between delta HS and the degree of cover it will be necessary to consider the total intercepting area in future measurement campaigns.

Snow duration in forests after low to moderate severity burn: Does tree size matter?

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Forested land generates more than half of the total global runoff. After high burn severity fire, the immediate and short-term effects on forest canopy influence snow accumulation and ablation rates, which can alter the water provision in spring months substantially when water demands increase. However, in low- to moderate-severity burned forests, effects on snowpack are less immediately apparent and might be delayed, emerging over several years. In general, fire preferentially kills smaller-diameter trees while leaving at least some larger trees alive that are more resistant. Therefore, variations in tree size and forest density at scales between 1 and 10 m could cause differences in snow duration in post-fire environments at 1- to 10-m scales. We aimed to understand the effect of small-scale tree neighborhood characteristics and post-fire tree mortality on snow disappearance timing in an old-growth mixed-conifer forest in the Sierra Nevada, California, USA that burned at low to moderate severity. We used annual, spatially-explicit tree mortality and snow disappearance data collected at the Yosemite Forest Dynamics Plot (YFDP) three, four, and five years following the Rim Fire of August 2013. Snow disappearance timing was calculated from 63 HOBO Pendant loggers that were installed on a regular grid throughout the YFDP. Based on the locations of mapped and measured trees, and the results of annual tree mortality surveys, we calculated seven tree neighborhood metrics to describe the vegetation surrounding the HOBO locations. Tree neighborhood metrics were calculated at radii of 2.5 m, 5 m, and 10 m, and three of the seven metrics (density of live trees, density of snags, and mortality rate) were also calculated specific to five dbh classes. Litter and woody debris were collected throughout the year adjacent to each of the HOBO locations. We then developed linear mixed models (LMM) to predict snow disappearance timing as a function of the post-fire overstory vegetation structure, litter density and potential direct solar radiation (fixed effects) by modelling HOBO location and sampling year as random effects. Results indicate that variations in snow disappearance timing were influenced by the presence of big live trees (dbh > 60 cm) within the 10-m ring radius in combination with potential direct solar radiation, i.e., if large diameter trees were present, the duration of the snow cover was extended. In contrast, live large trees and logs in close proximity to a HOBO location (< 5 m), and an increase in litter fall due to delayed post-fire tree mortality had the opposite effect. These results highlight the importance of large diameter trees as individual structural elements in mixed coniferous forests, since they are more resistant to fire and can contribute to a sustainable water supply from snow-dominated forested headwaters after low- to moderate-severity fire.

Snow Cover Area (SCA) changes over semi-arid region using CMIP5 Multi-model Ensemble (Case study: Uremia lake basin, Iran)

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Snow cover has a significant role in surface runoff and groundwater recharge in mountainous and semi-arid areas, especially within the Uremia lake basin where is facing the danger of drying over the last decades. In recent years climate change impact snow variations distribution, snow cover, and runoff in different scales. Therefore, spatial and temporal monitoring of the snow-covered surface and the impact of these changes is necessary. In the current study, first, changes of snow cover (SCA) in the study area were studied using MODIS images from 2002 to 2014 by the NDSI index. Evaluation of mean monthly minimum temperature and number of frozen days at selected stations during the winter and the first month of spring coinciding with snow cover in the study area showed that in most of the stations, the mean monthly mean temperature and mean monthly minimum temperature increased and the number of frosts decreased. Comparison of changes in snow cover area (SCA) with changes in mean temperature, minimum temperature and number of days with a temperature of zero or below zero indicates an increase in the temperature and a decreasing trend of snow cover area (SCA) in the region. Subsequently, due to the changes in snow cover as an indicator of future climate change, during the 2021-2050 (SCA) period were investigated. For this purpose, 3 climate models from CMIP5 models (CCSM4, CSIRO-Mk3.6 and Had GEM-ES) under two radiation emission scenarios (RCP4.5 and RCP8.5) with 0.5 * 0.5 a spatial resolution was used. The study aimed to investigate how the snow range is extended and by what means its coverage level in future periods can be indirectly determined. To do so, first, temperature gradient with monthly elevation in the period (2014) at the regional level was drawn using the temperature threshold of 2.4 for snowfall in the region, from December to March, respectively, by which the corresponding height to the snow-covered levels are specified. Besides, the elevated levels of snowy peaks in the region have been compared with the obtained elevations to control and ensure the accuracy of the obtained elevations. Next, to obtain changes in the snow cover level in the coming period, the average monthly temperature resulted from the above models for RCP4.5 and RCP8.5 scenarios in 2021-2050 periods are applied to the monthly temperature-altitude gradient equations. The results transferred to the hypsometric curve and compared with the results of the snow level measurements in 2014. Accordingly, the forward and backward coefficients of the snow levels are obtained monthly in the future period. By applying the above coefficient, the snow cover level was obtained in the upcoming period. The results showed that the temperature of the area during the period 2021_2050 is expected to increase and consequently the snow cover level will decrease based on the hypsometric study. As the temperature rises, the snow surface area decreases so that it could affect the region's water reservoir in the future.

Multi-year evaluation of a distributed data-assimilation snow model (S3M v 3.1) and implications for hydropower-hydrologic modeling

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Snow-cover distribution and snow-melt timing are key drivers of water supply in mountain regions, but their estimation is still challenged by large spatial heterogeneity of snowpack and low density of measurements. By focusing on two dammed, glacierized headwater basins in Valle d'Aosta (Italy), we evaluated the performance of a distributed, one-layer snow model (S3M v.3.1) in reconstructing basin-wide, pixel-wise, and point estimates of Snow Water Equivalent (SWE), snow depth, and bulk-snow density. Besides a standard open-loop simulation in which the model reconstructs snow dynamics solely based on external inputs, S3M can assimilate maps of snow depth and SWE based on ground-based measurements and MODIS. This option allowed us to assess the impact of assimilating each of these data sources on model predictions. The comparison between open-loop and assimilation-based maps over water years 2015 to 2018 showed that the former systematically underestimated peak SWE due to precipitation under catch, a problem that assimilation effectively solves. Model's estimates obtained by assimilating only snow-depth or SWE maps are significantly different. Simulations of inflow to the reservoirs in these basins obtained by coupling S3M with a full hydrologic model (Continuum) also showed significant differences. Overall, these results point to water-supply and hydropower forecasting being sensitive to the choice of the data-assimilation source.

Assimilation of snow depth maps from satellite photogrammetry in Crocus in distributed geometry

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Several methods are now available to map snow depth in mountainous area from drone, aircraft and satellite. Assimilation of snow depth measurements can be used to improve snowpack modelling in regions where meteorological forcing is generally poorly known. We present a spatially distributed assimilation scheme of snow depth maps in the detailed snowpack model Crocus. Snow depth maps are obtained from satellite stereo imagery (Pléiades) over a 115 km² alpine catchment in the Pyrenees and assimilated with a particle filter in Crocus. The benefit of the assimilation is evaluated with independent Pléaides snow-depth maps and maps of the snow melt-out date calculated from time series of Sentinel 2 snow cover maps.

Exploiting machine learning techniques for monthly runoff prediction in a mountain basin in the Andes range

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Snowmelt is the main source of water for human consumption and productive activities in the Central Andes range region, an area characterized by an arid climate. The monthly and seasonal flow forecasting plays an important role in water resources management. Machine learning techniques for flow prediction have recently observed a high degree of development and received special attention within the domains of water management and water research. Support vector machines are data-driven models based on learning systems. The aim of the current study is to investigate the performance of these techniques, in particular the Support Vector Regression (SVR) in predicting the monthly discharge with one-month lead time in the Tupungato basin in the Central Andes of Argentina. This methodology has never been applied before in this mountainous region. Different inputs and data splitting combinations were analyzed in order to find an appropriate model that be able to fit the observations. The models were forced with in situ meteorological data and remote sensing (MODIS) for estimation of snow cover. To evaluate the model performance five different metrics of common use in hydrology, all of them relating observed and simulated flow rates, were computed: the coefficient of determination (R^2), the mean absolute error (MAE), the Root Mean Square Error (RMSE), the Index of Volumetric Fit (IVF), and the Nash Sutcliffe Efficiency (NSE).In order to have a benchmark for comparison, a conventional auto-regressive moving average (ARIMA) model was also fitted. One-month lead forecasts obtained with the proposed SVR model outperformed the ARIMA model systematically for all tested combinations and splits. The results showed a significant improvement in model performance. The R^2 for the ARIMA model was 0.43 while the R^2 for the SVR models were above 0.77 in all cases (models and splits), with a maximum of 0.90. SVR models proved a promising approach to support water management and decision making for productive activities in the Tupungato basin.

Keywords: Support Vector Regression, Flow forecasting, Andes range, Machine Learning Techniques

Water availability forecasting of the Tien-Shan Rivers for different periods using remote sensing data

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The flow of the Tien Shan mountain rivers during high water and its months is highly variable from year to year, so its early forecast is important for a number of consumers (hydropower, water), and, first of all early warning the population about possible emergencies associated with high water (floods) or low water (droughts).The main sources of food for Mountain Rivers are melt (snow and ice), rain and groundwater. The Central Asia Rivers are fed by melt runoff of snow and glacier water on 80-90%. Thus, the use of methods based on information on snow reserves in the zone of river flow formation provides high-quality and reliable forecasts for the flood period. Information on the snow cover area for various basins of the Tien Shan Rivers in the zones of runoff formation from the MODIS images was used to predict water availability for the entire flood period of its months and decades. The availability of daily information about the area of snow cover and the daily course of snow melting were made possible through to the use of the MODSNOW program, which has developed algorithms for removing cloud cover from MODIS satellite images. MODSNOW can be used to automatically process MODIS snow cover data for various mountain river basins, including cloud cover removal (estimation of the actual pixel coverage under a cloud cover).The obtained correlation dependences of average water discharges during the flood period with snow cover area (SCA) are highly close dependencies (R) 0.73-0.92. For different geographic location, altitude and catchment area, climatic features, the dependences of the average monthly water discharge for high water months with snow cover indices (SCI) showed different results and correlation coefficients (R) were 0.51; 0.83.The results make it possible to estimate the water content of the Tien Shan Rivers for different periods of lead time during the flood period on the basis of snow data from MODIS images. The proposed equations for calculating the runoff forecast for the flood period were introduced in 2015 into the operational hydrological forecasting system of Kyrgyzhydromet and are used to compile hydrological forecasts.

Does a shift in precipitation from snow towards rain lead to a decrease in mean streamflow? - Comparison of MOPEX Dataset and CAMELS Dataset

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Changes in snowmelt water and rainfall have important implications for the replenishment of runoff and groundwater recharge in the western US, Canada and other regions in the world. Previous research, using the MOPEX catchment hydrology dataset, showed that catchments with higher snow fraction have higher mean runoff coefficient, for the same climate. It also showed that in years with higher snow fraction, there tended to be higher streamflow for a given precipitation. However, the MOPEX data covers only a limited range of US catchments, and has very limited coverage of the Rocky Mountains, a major source of snow-fed water resources. Thus, the generality of those results is unclear. In this research, we compared the results from MOPEX with those from the more comprehensive CAMELS Dataset, also in the USA, using the same methodology. We found the same conclusion, that catchments with higher snow fraction have higher mean streamflow. According to the between-year sensitivity analysis of normalized annual runoff to annual precipitation falling as snow, we also find that years with more snow tend to have more streamflow. Most catchments with snow fraction above 15% have this positive sensitivity. This indicates that annual streamflow of catchments with higher snow fraction varies directly with the annual snow fraction. The results from analyzing the CAMELS data generally confirm the previous results obtained from MOPEX. With climate warming, it is almost certain that there will be a future shift from snow towards rain. The implication of our results is that, unless there is an increase in precipitation, it is possible that mean streamflow could decrease in future. In further research, we will consider what are the hydrological processes responsible for precipitation phase partitioning changing with climate warming to influence catchment response. This would enable a physical basis for future projections of the magnitude of this change.

Quantification and visualization of changes in runoff timing and changes in runoff seasonality in snow-dominated river basins

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The accumulation and melt of seasonal snow covers control runoff seasonality, water availability and flood timing in alpine river systems. An earlier onset of snowmelt in spring as a consequence of a warming climate represents a much-noticed effect on alpine river runoff. In the framework of this study, we assess different analytical tools to quantify changes in runoff/flood timing and seasonality of river runoff in snow-dominated river basins. Besides raster hydrographs, which provide a quick first insight into inter- and intra-annual variabilities, we inter alia assess timing and magnitudes of annual/seasonal maxima, determine phase lags between yearly hydrographs and calculate changes in quantiles over time. Focus is on the European Alps. The analysis goes along with the development of an interactive Web App, which ensures easy access to analysis results and facilitates the determination of assets and drawbacks of different analytical tools.

Historical reanalysis of the snow water equivalent in Trentino

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Climate change is posing an increasing concern and the extreme weather events, be it flooding or drought, attract the attention of the public ever more frequently. The awareness of a change in the climate compels the Public Administration to provide itself with adequate tools to predict and possibly manage the impacts of these events on the environment.
Principally the management of drought is becoming ever more important: on this respect, the quantification of the availability of water deriving from snow melt is particularly interesting. The snow, in fact, is like a natural reservoir of water that provides a water contribution with gradual release.
Given the importance of snow accumulation in the hydrological cycle, this paper proposes a procedure to the estimate the snow water equivalent (SWE) in Trentino based on the physical model SnowMaps (Dall'Amico et al, 2011, 2018). Starting from the meteorological dataset of Autonomous Province of Trento, a reanalysis of snow evolution in Trentino has been realized from the season 2007-2008 to 2017-2018, at 250 m resolution and daily aggregation, reconstructing the variables SWE, snow depth (HS) and new snow accumulation (HN). The results show a general good fit ($R^2 > 0.75$), both in terms of HS and in terms of SWE, with ground measurements and provide also interesting insights on possible errors in the historical measurements.
Finally, a statistical analysis of the maps was realized, calculating the percentiles of the snow distribution for each day of the winter and SWE's aggregated values for determined areas and time intervals. This dataset becomes a very useful tool to compare the snow quantification and its water equivalent in a catchment in whatever lapse of the winter with the historical statistics, thus highlighting anomalies and anticipating possible drought conditions.
This operating procedure could become a good indicator of local climate change and a practical support for water resource management.

Past and future trends in snow water equivalent along an alpine slope

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Snow water equivalent (SWE) is an important variable for cryospheric and hydrological investigations, especially in the context of climate change. Often, continuous time series of SWE measurements are limited to specific locations, which are equipped with appropriate sensors (e.g. snow pillows). In contrast, human observations can be distributed more spatially; however, the lengths of such time series are limited by the considerable sampling effort. In this study, we used SWE measurements that were taken regularly by observers from 1985 until the present. SWE was determined at the south facing slope of the Gradenbach research site close to the main ridge of the Austrian Alps between 1.200 m a.s.l. and 2.100 m a.s.l. in vertical steps of 100 m. The measurements were taken once a week when feasible and at a minimum every 2 weeks. We used our SWE measurements and meteorological long-term data sets (ÖKS15 data from the Climate Change Centre Austria) of air temperatures (daily mean, minimum, maximum), precipitation and global radiation to develop a statistical model (neural network). It estimates SWE based on data from the nearest grid point in the ÖKS15 domain. We then applied the model to the time period available from ÖKS15 to predict daily SWE from 1949 to 2099 for each elevation step. Grouped by elevation and month, the data were used to determine temporal trends. The Mann-Kendall nonparametric trend test was used to calculate these trends in SWE and their significance. In order to identify trends with various lengths, a variable window size was defined that convolves over the available time period. In our contribution, we discuss the challenges of building such a statistical model based on our results and its further application in predicting trends in SWE and other related snow variables for mountain regions.

Towards a high-resolution long-term snow climatology for Germany

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Several efforts were made in the past to elaborate a snow climatology covering various parameters and areas of Germany. For instance, snow cover duration parameters and maximum water equivalent of snow were estimated on a 1 km^2 grid covering Germany within the project "Hydrological Atlas of Germany". The analysis was based on roughly 550 quality-proofed station observations for the period 1961–1990. Because of a high year-to-year-variability and the length of the investigation period, no clear statements on any trends could be made. Another project in the framework of the KLIWA (Climate Change and Consequences for Water Management) programme analysed the long-term behaviour of several parameters characterising snow cover duration as well as the maximum water equivalent between 1951 and 1996. These studies were performed for the territories of the federal states of Baden-Wuerttemberg and Bavaria. The previous efforts, however, did not lead to a long-term snow climatology which considers longer and more recent periods and which covers Germany entirely. But longer analysis periods are required because of the high year-to-year variability observed for snow cover. At DWD, we now developed a long-term snow climatology for Germany. We analysed roughly 480 good-quality snow observations for the period 1951–2010 and grouped these data in so-called 'natural regions' based on the classification of the Federal Agency for Nature Conservation (BfN). For these regions, we investigated the same snow cover duration parameters as those used in the KLIWA analyses. Snow water equivalent was not considered because only very few good-quality observational time series were available. In order to also assess snow amount parameters, we considered mean and maximum snow depth. Region by region, we computed statistical quantities for every station, among others the mean values for winter (September–June) averaged over the 30-year periods 1951–1980 and 1981–2010. To determine possible trends, we then calculated the differences between both averages. The significance of trends was estimated by comparing the slope of the regression line with the ratio between standard deviation and mean value as a measure of natural variability. If at least 50 % of all stations within a natural region showed significant trends, the trend for the region in question was assumed to be statistically significant. For all of the natural regions, our study found no increase in any of the investigated parameters. In some regions, several snow cover duration parameters (duration of snow cover, time of snow cover and date of maximum snow cover) as well as the maximum snow depth during a winter period showed decreasing trends. No trend in any direction was found for mean snow depth. In construction industry, for instance, there is a need for a snow load climatology with high spatial resolution. Therefore, our next step is to elaborate a gridded snow depth and snow water equivalent climatology using an optimal interpolation algorithm. All daily observations available for Germany will be used for gridding, irrespective of their degree of completeness. The quality of the resulting product will be assessed using the jackknife resampling method.

Session 3: Cryospheric processes - observations and modelling

The state of Art of Modelling Permafrost and Freezing Soil

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This contribution summarizes the recent developments in modelling the freezing soil and permafrost, and introduces some applicative examples. Freezing soil modelling is absolutely important not only for modelling permafrost conditions, but also for seasonal variations of soil characteristics, which cause both runoff and evapotranspiration. Soil temperature also affects snow accumulation and its metamorphism and, therefore, is extremely important to have it right. If permafrost contains ice then, hydraulic conductivity, soil water retention curves and soil thermal capacity are all affected and change in some considerable manner the whole energy exchange between soil and atmosphere. Most of the approaches for permafrost are based on a main assumption: freezing is equal to drying, while vapor transport is neglected and ice expansion is, as well, neglected. We discuss to which extent these hypotheses can be considered valid also by comparing cases on Earth and Mars. Since the system soil-ice has a huge thermal inertia, we will also discuss some simplifications that can be used to obtain long term simulations, whilst with approximate results.

Canopy structure controls on energy fluxes to the forest snowpack: observations and modelling

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The complex dynamics of snow accumulation and melt processes under forest canopy entail major observational and modelling challenges. Of particular importance is the radiation transfer through the canopy to the snow surface, which varies considerably in time and across small spatial scales. Increasingly detailed canopy structure datasets are becoming readily available and can be leveraged to improve representation of physical processes in forest snow models. Evaluating model performance at the level of individual processes requires spatially distributed measurements of sub-canopy energy fluxes. To this end we have developed novel observational systems designed to capture spatial and temporal variations of incoming short- and longwave radiation, and air and snow surface temperatures in subalpine and boreal forest stands. For all measured variables the combination of fixed sensor arrays and sensor assemblies mounted to either a motorized cable car system or a handheld stabilized gimbal yielded 1) time series at point locations, 2) spatiotemporal patterns along linear transect, and 3) snapshots in time of 2-dimensional spatial distributions. Concurrent simulations of the forest snowpack at high resolution (2m) were obtained with FSM2, a point-scale snow model of medium complexity that includes coupled energy balances of the sub-canopy snow cover and the canopy. By comparing modelled sub-canopy energy fluxes to observational data, the performance of alternative canopy representation strategies within FSM2 could be assessed at the level of individual snow energy balance components. Our data demonstrates the benefit of incorporating detailed spatial patterns of canopy shading on the snow surface for reproducing snowmelt dynamics in discontinuous forested environments. High resolution simulations resolving these effects provide an optimal basis for validating and improving the representation of forest snow processes in land surface models intended for coarser-scale applications.

Impact of snowfall distribution on the assimilation of passive microwave data in a snowmelt runoff prediction model

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Mountain snowpack represents a natural water reservoir. It stores water from precipitation during winter and releases water to the rivers during the snowmelt in spring and summer. In Northern Sweden, snow is an important resource for several sectors of the society including reindeer herding, tourism, ecology and hydropower. In mountainous catchments with hydropower reservoirs, the hydropower production is strongly linked to the amount of snow in the catchment, to the snowmelt timing and runoff available for reservoir filling. Underestimations of snow and snowmelt runoff volumes at the end of the spring and in the early summer can impact reservoir regulation with consequences for the energy production and economic benefit. Furthermore, prolonged snowmelt season in combination with intense summer rainfall events can generate high flows with potential for flooding and risk of damages and loss of life. Therefore, it is essential to have an accurate estimation of the snow storage and spatial distribution, for snowmelt runoff predictions. In mountainous catchments snow spatial distribution is highly variable due to the complex interaction between precipitation, wind, vegetation and topography. This variability affects snowmelt timing and patterns. The availability of spatially distributed ground observations reflecting snow variability is often limited. To overcome these limitations, hydrological modelling in combination with data assimilation of remote sensing observations can be used. The effect of this combination on snowmelt runoff predictions is, however, little understood. In this study we investigate the potential of assimilating satellite microwave data to improve snow water equivalent estimates accounting for snow spatial variability. We model the seasonal snow water equivalent distribution in the Lake Överuman catchment, Northern Sweden, for the snow season 2018-2019. Simulations are performed using the semi-distributed hydrological model HYPE in combination with the CMEM transmission model to assimilate satellite microwave data. The snowfall distribution within each calculation sub-unit of the model is estimated based on the distribution of wind shelter factors within the unit. The units are formed by 2.5x2.5 km^2 grid cells, which are further divided into hydrological response units based on elevation, vegetation and aspect. Simulations are compared with ground penetrating radar-based snow water equivalent observations acquired along snow survey lines in the catchment. Preliminary results show that the snowfall distribution model improves the model results with regard to the spatial variability of snow within each model sub-unit compared to benchmark simulations without the wind effects. The impact on the estimation of the total catchment mean snow water equivalent and snowmelt runoff volume, based on assimilating traditional satellite-based retrievals and passive microwave brightness temperature, will be further assessed using both the snow survey data and reservoir inflow observations.

The influence of snow patch size on local-scale advection of sensible heat towards a patchy snow cover

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Snowmelt is poorly modelled by climate and weather models, especially when the snow cover becomes patchy. This causes problems for, for instance, hydropower stations. One of the uncertainties in modelling snowmelt of a patchy snow cover, is caused by the local-scale advection of heat, which transports sensible and latent heat originating from bare ground towards the snow patches. Regarding this process, the role of patch size for snowmelt has shown some contradicting results by previous studies. Therefore, this study aims to provide insight in the role of snow patch size during snowmelt by performing direct numerical simulations. This enables us to study the fluid dynamical aspect of a turbulent flow above a constant patchy snow cover in detail. However, due to the computational constraints of direct numerical simulations, realistic cases will need to be simplified. In this study, the measurements performed on a single snow patch by Harder et al. (2017) are simplified and used as starting point for investigating the fluid dynamical influence of snow patch size on snowmelt due to local-scale advection of sensible heat. However, initially the flow characteristics of the simulations are compared with previously done measurements as well as measurements done during a field campaign in Finse, Norway. The simulations show similar behaviour as the measurements, regarding the development of the internal boundary layer and the leading-edge effect. For the role of snow patch size, it was found that for a doubling and quadrupling of the average snow patch size with an unchanged snow cover fraction, the total snowmelt reduced with respectively 15% and 25%. The length of the snow patches was the main cause of this reduction, since the sensible heat fluxes at the leading edge of the snow patches are similar for each snow patch. Also, the decay of the sensible heat flux downstream from the leading edge is found to be independent of patch size. Therefore, at the downwind edge of longer snow patches, the sensible heat flux is lower, reducing the total snowmelt when snow cover fraction is constant. Furthermore, stability was only found to have an indirect effect through the wind field on the sensible heat fluxes. This stability effect was, next to the general behaviour of the system, captured by the model we developed and consists of just a few equations. This simple model describes the behaviour of the height of the internal boundary layer and sensible heat flux as a function of distance from the leading edge. It is also attempted to match the behaviour of the simple model with the measurements done in Finse and previously done measurements. Overall, this study has provided a first step towards a more thorough understanding on the role of snow patch size on snowmelt due to local-scale advection, which can be used in future modelling studies.

Session 4: Snow in semi-arid environment

A 55-yr trend analysis of snow torrentiality and aridity in a Mediterranean mountain range, Sierra Nevada, Spain

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Climate variability and a warmer and drier regime in Mediterranean regions usually result in several accumulation-ablation cycles of the snowpack in high mountain areas. Despite observations in these environments do not conclude on a significant decrease of precipitation on an annual basis, several works point out trends of increased torrentiality of precipitation on the seasonal and event-based scales, which largely impacts the snowfall occurrence and persistence and, hence, the hydrological regime both in mountain rivers and downstream. This work presents the results of the 55-yr trend analysis of selected variables that drive or describe the snow occurrence and persistence in Sierra Nevada, Spain, on different time scales, together with a zonation in this area based on the shifts found in the torrentiality and aridity indicators of the snowpack dynamics. The joint use of observations and physical modelling allowed for a spatial distribution of the target variables and indicators, and an initial assessment on these shifts' impacts on streamflow regime on different time scales. Sierra Nevada is a 4600 km2 high mountain area in southern Spain (up to 3479 m a.s.l.) with a longitudinal axis parallel to the Mediterranean Sea, and an Alpine climate highly influenced by the Mediterranean coastal conditions just 40 km South and the proximity of the African continent. The results show a highly variable annual and, to some extent, decadal regime of snowfall (occurrence and amount), lacking trend in most of the cases, but an increase trend of the mean and maximum temperature on different time scales. The shift towards a more torrential precipitation is found in a major fraction of this study area, but non-negligible gradients are found both in the East-West and North-South axes. The increase of dry (and longer) spells impact the water release to the streamflow and groundwater. The resulting trends envision a future scenario in which streamflow will very likely keep on decreasing due mostly to torrentiality rather than to significant decrease of precipitation and snowfall, which is not generally found. Discussion of the major drivers for this impact and the differences among zones is also provided.

Process-oriented streamflow characterization in mountain rivers of semiarid areas: Sierra Nevada, Spain

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The storage capacity of snowpacks is one of the major sources of water during spring and/or summer season in mountain areas; in Mediterranean and other semiarid regions, this supply is extremely crucial and can be the only water source to streamflows for long periods. To better understand the significant drivers of the observed change of hydrological regime in many mountain rivers, a process-oriented approach is required due to the concomitant occurrence of different processes whose effects interact and propagate along the cascade from atmospheric conditions to runoff and baseflow generation in these areas. The snow dynamics is especially affected by the observed trends of precipitation, temperature, and dry spells, and the impact on the partitioning of water fluxes from the snowpack highly alters the river flow regime, without one single forcing due to the large nonlinearity of their interactions. This work presents the characterization of streamflow events in mountain rivers of semiarid areas based on a process-oriented approach from the identification of the major sources/sinks of water in the snow-dominated headwaters of different basins in the Sierra Nevada area, in southern Spain, within an altitudinal range of 1000-3479 m a.s.l. For this, a 20-yr series of daily flow in a gauged point in the Guadalfeo River that drains the southwestern area of Sierra Nevada is analyzed together with meteorological time series and the simulation of water fluxes from the snowpack by the physically-based model SNOWMED. The resulting excess and deficit events are then classified following the dominant driver/s underlying, and associated to selected descriptors of the observed weather and snow states. The classifier algorithm is finally tested against the available flow observations in other areas in Sierra Nevada different from the Guadalfeo River basin. The results not only deepen the understanding of snowpack-streamflow interactions in these semiarid regions but also provide an assessment on what expected shifts of the hydrological regime are more likely to develop under the impacts of climatic trends in these snow areas.

Can we learn from "snow islands" about future trends in different snow regions in the world?

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Mountain regions are especially vulnerable to changes in the climate regime due to the influence of global warming on the snow occurrence and persistence. Beyond this general impact on a global scale, very different dynamics can be found for snowpacks among the different snow regions in the world: latitude, altitudinal range, sea influence, radiation components, cloudiness, air moisture, winds, vegetation, microtopography, and even soil structure can result in a wide range of snowpack dominating dynamics on the local scales. Moreover, exposure to highly variable conditions makes the semiarid regions special examples to study the impact of the observed climatic trends on their snowpacks and estimate the potential future behaviour in other regions. Particularly, there are snow sites in the world where snow, although being recurrent on an annual basis and relevant for the hydrology and water resources availability downstream, constitute isolated areas within no-snow regions due to strong topographic gradients, which makes them similar to “snow islands” surrounded by other very different climatic conditions. These sites are prone to earlier suffer the impacts of global warming and constitute strategic observatories of potential changes. This work presents the results of a previous trend analysis of the snow regime and its major drivers in Sierra Nevada, Spain, in the broader context of comparison to other significant snow domains in the world, as one of these “snow islands”. Different zones are presented in terms of their representativity of different snow domains in relevant regions in the world, and the observed trends and their dominant drivers are analysed as potential indicators of changes and their estimated thresholds where available. For this, a dataset of 55-yr of meteorological observations and simulations of selected variables representative of the snow regime was used to retrieve decadal, annual and seasonal trends across the head areas of five different catchments in Sierra Nevada. A multivariate analysis was done to validate the zoning and their comparison to selected snow sites over the world from data available in refereed publications. The conclusions identify the relationships on a global basis and provide an assessment of early-estimations of potential impacts in the future.

Snow-Atmosphere Interface

Keynote lecture

"The effect of changes in snow seasonality on hydropower"

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Hydropower makes up about 16% of electricity generation globally but close to 100% in many mountainous countries. Changes in river runoff have been observed in many snow-dominated river basins in several countries. Both total discharge and seasonality show changes in river basins that supply water for hydropower. An increase in winter runoff and decrease in summer runoff related to decline in snow cover is observed in many areas. However, the pattern is variable and, in some regions, contrasting patterns have been observed in neighbouring valleys. Changes have been recorded in Switzerland, Canada, Iceland and Asia. Projections show that runoff will change in many areas in future decades including Switzerland, Canada and North-western USA. Changes in the cryosphere are not limited to snow cover, and glaciers also show significant decrease in mass, which leads to an initial increase in runoff and hence input to hydropower followed in due course by a decrease in runoff.

Session 1: Prediction of snow melt and run-off

Comparison of SWE at basin scale with measured discharge at basin outlet by separating the contribution of rainfall and snowfall

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Climate change is increasing conflicts due to the limited availability and different uses of water resources. Water management becomes a crucial aspect for dealing with future challenges related to water scarcity and extreme events. In this context, snow melting forecasting is an important variable, not only because it belongs to the hydrological cycle, but also because it has several applications, like for hydropower to optimize the production planning, and for civil protection to anticipate possible flooding due to rapid melting.

Traditionally, snow water equivalent (SWE) estimation at basin scale is performed by spatially interpolating in-situ measurements according to selected predictors, namely morphological variables like elevation. This methodology is affected by some limitations, like the cost of measurement campaigns and the impossibility to extend it to ungauged basins. Physically-based snow models (e.g. Endrizzi et al, 2014) may solve these limitations for SWE estimation. However one question still remains to be addressed: how should one compare the quality of the SWE estimate at basin scale?

In fact many models and methodologies have been tested at point scale, however some applications, like hydrological balances, are more interested in a good estimate at basin scale rather than at point scale. So the question may be posed differently: is there a measurement of SWE at basin scale?

This work aims to address this question by proposing a methodology to obtain a measurement (say, the "best estimate") of SWE at basin scale by using discharge data in a natural basin, i.e. not affected by reservoirs upstream. We propose a methodology to separate the discharge coming from rainfall from the discharge coming from snow melt and estimate the difference of SWE necessary to justify the discharge in a time interval. Applying this methodology in back-analysis up to the beginning of the snowfall period it is possible to obtain the "best estimate" of SWE in the basin. The same methodology may be applied in a catchment where a reservoir is present when the levels of the water are known.

We apply this methodology in an alpine basin characterized by the presence of a river discharge sensor (hydrometer) and a natural basin upstream. We use Mysnowmaps (Dall'Amico et al, 2018) as the physical model to calculate the rain and snowfall contribution in the discharge and obtain the quantity of water flow that most likely depends on snow melt with a 15 days time interval. Finally, this water flow coming from snow melt is compared with the difference of SWE from the snow model in the same time interval.

The results show a good performance of Mysnowmaps SWE with respect to the water flow coming from snow melt.

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Protective function of the snowpack during rain-on-snow events

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Rain-on-snow (ROS) events have been in the focus of hydrologists for the last decades. This is because they often cause severe flooding during the winter period. Prediction and modeling of hydrological response from such events are still challenging because the rainwater propagation through the snowpack has not been fully understood yet. The runoff response is mostly related to snowpack properties and meteorological drivers. However, detailed snowpack properties are usually unknown for the entire catchment. The snowpack has an ambiguous effect on the hydrological response. Part of the rainwater can be stored inside the snowpack which might result in less amount of rainwater in the runoff. On the contrary, rainwater usually accompanied by a relatively warmer air can cause additional snowmelt, which can significantly increase snowmelt rates and thus the runoff volume. Therefore, the main objective of the study is to better understand how meteorological and hydrological conditions are related to different hydrological responses. We identified 424 ROS events in the period between 2004 and 2014 within 15 mountain catchments in Central Europe (Czechia). These catchments are located in two mountain ranges at elevations from 400 to 1600 m a.s.l. with area ranges from 2.6 to 181 km2. The identified ROS events were further categorized into four groups according to the runoff response. We found out that almost half of the identified ROS events (48%) did not cause any significant event runoff increase (Group 1). Other 17% of ROS events reached only from 25% to 50% of the baseflow (Group 2) and 21% reached 50-75% of the baseflow (Group 3). The last 14% represent the events with a significant runoff increase exceeding the 1-year return period (Group 4). We also found a significant difference in the ROS occurrence between studied mountain ranges. In all catchments, though, the snowpack mostly had a protective function against floods, by absorbing most of the fallen rain. The events with the highest increase in runoff were mainly related to the higher air temperature and associated snowmelt. However, the ratio of meltwater contributing to the runoff was not much different among the groups. The meltwater contributes to the runoff at the beginning of the event 10% (Group 1) to 20% (Group 4), but the ratio increases in time and reaches 50% (Group 1) to 60% (Group 4) for the entire event. We also analyzed runoff volumes and times to peak of all events. The analysis show that the time to peak increases with the total runoff volume. We conclude that snowpack protected the catchments against significant runoff increase, because it absorbed most of the incoming rainwater. This protective function weakens with increasing snowmelt rate. Nevertheless, we identified a smaller number of ROS events causing significant runoff increase.

A physics-based approach for efficiently parameterizing turbulent heat fluxes during rain-on-snow in support of operational, probabilistic melt forecasts

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Rain-on-snow (RoS) can produce substantial snowmelt when there are coincident high winds. The combination of warm, moist air and high wind speeds produces strong turbulent energy fluxes to the snowpack. Accurate representation of these turbulent fluxes usually requires energy-balance solutions. In time-limited, operational forecast settings, energy-balance solutions represent a considerable computational expense limiting the number of available simulations. Yet turbulent flux calculations are highly sensitive to uncertainties in forecast data and model parameterizations so that using a multiple member, ensemble approach should be considered. This study introduces a fast method for calculating turbulent fluxes during RoS based on air temperature and wind speed, which compared very well to a full energy balance solution. These streamlined turbulent flux parameterizations were established for several different roughness lengths and forced with perturbed air temperature and wind fields to account for forecast and model uncertainties during a 24-hour RoS event across Switzerland. The resultant turbulent fluxes were used to modify melt from a deterministic energy balance snow model run producing an ensemble of 459 simulations with associated probabilities. Streamlined melt simulations were produced an average of 30 to 35 times faster than full energy-balance simulations. Probabilistic forecasts derived from the two methods were almost identical. Across a range of exceedance levels root-mean-squared-differences never exceeded 3 mm/day and bias magnitudes were all less than 1 mm/day.

Influence of input data sources on SRM seasonal snowmelt runoff prediction

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The SRM Snowmelt-Runoff Model has been used increasingly in recent years to simulate and forecast runoff from snow and glacier dominated catchments in the Himalaya–Karakoram–Hindu Kush region. One of the reasons is its aptness for remote sensing input data, which enables modelling of large and remote catchments where ground data is scarce. Over the time however, some remote sensing products like MODIS or TRMM have been superseded by upgraded versions or successor products, which motivates the present research on the sensitivity of model results to changes of input data sources that can also be interpreted as part of an uncertainty analysis. Upper Chenab catchment is used as a case study to test the influence of different gridded precipitation products and MODIS snow product versions v005 and v006 on the prediction of seasonal flows as well as on the relative flow contribution from rain, snow, and glaciers, which is an important indicator for resilience to climate change. The upper catchment of Chenab River, being the most eastern river of the Indus Basin which flows are allocated to Pakistan under the Indus Water Treaty, is mainly located in Himachal Pradesh province of India. Flow contribution in the period 2000 – 2013 was found to be about 50% from snow, 37% from rain, and 13% from glaciers. The catchment was modelled by SRM+G which is an Excel implementation of original SRM with an additional glacier melt component that has been developed for Punjab Irrigation Department of Pakistan in order to forecast Kharif (April – September) seasonal flows of the Chenab River at Marala barrage. The model is calibrated with NOAA's RFE v2.0 South Asia precipitation and MOD10A1/MYDA10A v005 Snow Cover Daily data products. Overall model accuracy for the period 2000 – 2013 is given by a coefficient of determination R2 of 0.86 and a relative volume difference DV of -1.3%. Sensitivity on precipitation input was tested by forcing the model with RFE v2.0 Central Asia, CMORPH, TRMM, IMERG, and APHRODITE gridded precipitation products without any change of the originally calibrated model parameters. Not surprisingly, model performance diminishes depending on each product. On average, R2 reduces to 0.79 and DV worsens to -6.3%. The relative contribution of flow components however is much less affected. Standard deviation considering all evaluated precipitation products is 2.7%, 3.4%, and 0.7% for snow, rain, and glacier respectively. Similarly, the change from MODIS version's v005 Snow Cover Daily to version's v006 NDSI resp. Fractional Snow Cover product results in a modest change of flow components to about 55% snow, 34% rain, and 11% glaciers. However, DV increases to 9.3% indicating a substantial overestimation in the prediction of seasonal flows. Thus, relative flow component distribution seems to be quite robust to changes of data sources, while absolute seasonal flow volume is more sensitive to the data sources and will in most cases require a re-calibration if the input data sources are changed.

Keywords: SRM Snowmelt-Runoff Model, Seasonal Flow Prediction, MODIS, Gridded Precipitation Products

Qualification of an operational snowmelt model against a composite dataset

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Motivated by a better management of the water resources in the short and medium term in the French Alps, an operational tool derived from a 4-parameter degree day snowmelt model was developed by TENEVIA with the support of CNR. That model, named OPEN, is designed to quantify and anticipate the accumulation and melting of snow and glaciers, according to a bunch of various data. The tool models the partially glacierized upper Arve catchment. Simulations of the snowpack and glaciers were realized using the AROME 0,025° meteorological forcing (Météo France) from 2010 to 2016. The temperature is interpolated on the thinner mesh of the DEM according to an altitudinal gradient. The snow/ice melt models use a semi-distributed approach gathering land surface by elevation range and nature of the soil. Masks were thus applied on the DEM to differentiate the degree-day parameters. Two calibration processes can be used to determine the Melting parameters. The reference calibration procedure is based on the observed flows of some stations in the area (Chamonix, Sallanches, etc.) through a hydrological model. KGE (Gupta et al. 2009) and r^2 scores are then optimized using a Monte-Carlo method and a gradient descent algorithm. Calibration can also be performed from any estimation of the snow water equivalent derived from various field data such as described hereafter. OPEN methodology aims to adjust the snowmelt model assimilating field data about the snow conditions. These data contain observations as snow cover area (SCA) information derived either from satellites images originating from MODIS sensor (NASA) or from camera pictures of the Aiguilles Rouges range. That latter images are processed by the Tenevia CamSnow product (SCA measurement by image processing analysis). MODIS images from Terra and Aqua satellites are merged to increase their reliability. OPEN also uses in-situ measurements of snow depth selected for their trustworthiness and realized by Météo-France or winter sport resort located either in the catchment or close to it. These measurements are converted in snow water equivalent via snow bulk density model (Jonas et al. 2009, Sturm et al. 2010). These observed data have diverse resolutions, locations and temporal availabilities. They give complementary but sparse information. The assimilation process is a daily one to answer to operational purposes and considers the latest twenty days of observation. Results of this study show that despite the lack of in-situ data to qualify the real performance of the model, we obtained promising outputs in terms of snowpack and flows at the outlet when assimilating all the available data. A deeper work dealing with yearly glacier mass balance measurements led by the IGE on the Argentière glacier (GLACIOCLIM Database) show the ice melt model provides excellent outcomes also. However, sparse or contradictory observations sometimes produce discontinuities in the snowpack. Further works are in progress to improve assimilation, in order to better consider the proper characteristics and reliability of each data.

Session 2: Prediction of snow melt and run-off

Understanding runoff generation processes in meltwater-dominated catchments by means of stable water isotopes

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Mountain catchments are fundamental landscape units to study runoff generation processes whose understanding is critical to develop effective measures for drought mitigation and flood prevention. Particularly, high-elevation and high-latitude catchments, dominated by meltwater inputs (snowmelt and glacier melt), represent important sources of freshwater and are particularly vulnerable to climate change effects. A detailed comprehension of hydrological mechanisms in these environments is therefore pivotal both for flood risk assessment and for projection of future water supply and water resources management. In the last decade, several studies were carried out in meltwater-dominated high-elevation and high-latitude catchments in cold regions around the world, in different physiographic conditions and climatic forcing. Many of these studies were conducted based on an experimental or experimental-modelling methodological approach that took advantage of stable isotopes of hydrogen and oxygen, used as tracers to track water flow pathways through the catchment. These works contributed to get more insight into the hydrology of these systems, offering a description of a large variety of mechanistic and sometimes site-specific behaviours. There is, therefore, the need to summarize the recent findings and organize them in a coherent framework to obtain a comprehensive overview of runoff generation processes in meltwater-dominated catchments and, at the same time, to identify research gaps. In this work, we provide an overview on current knowledge derived by recent studies that applied stable water isotopes in high-elevation and high-latitude catchments. We collected more than 70 papers published between 2015 and 2019 in peer-reviewed journals. We focus and summarize the main findings obtained by these papers around the following key points: quantification of water sources contributing to stream runoff; role of snow and glacier storage on water availability and catchment hydrological response; role of permafrost thawing on meltwater input to stream; results of isotope-aided modelling to predict flood generation and project future runoff dynamics; estimation of catchment water age and transit times. We, then, highlight current limitations associated to the methodological approaches, provide possible solutions to overcome them, and identify research lines that can serve as a guide for future isotope-based studies of hydrological behaviour in meltwater-dominated, high-elevation and high-latitude catchments.

Keywords: stable water isotopes; melt water; snow; glacier; high-elevation catchments; high-latitude catchments.

The role of snowmelt to stream flow: a tracer-based hydrograph separation of the Sulden River in South Tyrol

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Snowmelt is an important contributor to the stream flow of alpine rivers in early summer. The amount of snow stored in the catchments varies from year to year and the velocity of melting snowpack to become melt water depends on changing meteorological parameters such as air temperature and radiation. Thus, the hydrometric response during snowmelt conditions is highly variable and leads to different snow melt contributions. In this context, tracer-based studies offer great potential to identify different runoff components and are useful for model calibration. However, tracer-based mixing models deserve further attention as representing the spatial variability of runoff end-members composition remains challenging. In this study, we estimated the snowmelt contribution at the Sulden River during early summer since 2014 by using a tracer-based approach with respect to electrical conductivity and stable water isotopes (d18O). The study area is the Sulden catchment in the Eastern Italian Alps (catchment area: 130 km²), where an automatic sampler collected daily water samples from May to October since 2014. For few days per year, the sampler followed also an hourly sampling approach to cover entire melt-induced runoff events. To represent the hydrochemistry of the runoff end-members, we sampled dripping snowmelt, precipitation at the event and monthly scale, spring water, and stream water before the yearly onset of snowmelt. Air temperature, precipitation, snow depth and snow cover data of the study area were acquired from weather stations of the Hydrographic Office of the Autonomous Province of Bozen-Bolzano and EURAC Research. During the snowmelt period in June, electrical conductivity dropped from winter baseflow values above 400 µS/cm to median values of 230 µS/cm and minimum values of 197 µS/cm, indicating dilution effects caused by melt water input. The isotopic depletion of stream water composition clearly showed the influence of snow melt water to supply stream flow in these periods as the median isotopic composition was at about -14.1 ‰ and reached about -15.5 ‰ in years with extensive snow cover. In this context, further analysis will focus on the tracer-based estimation of snowmelt contributions of snowmelt periods of different years and single events, and how these estimates may vary according to the definition of runoff end-members. In addition, we will elaborate the nivo-meteorological conditions initializing and sustaining the snowmelt period.

Challenges for the use of seasonal forecasts in Mediterranean mountain areas

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There is currently a number of European projects (MED-GOLD, CLARA, S2S4E, H2020_Insurance, VISCA, CLIMATE-FIT, SECLI-FIRM, PROSNOW, CLARITY) involved in the development of tailored and usable climate services (CS) that can facilitate the uptake and use of climate information and forecast by the final users. Within the CLARA project, the GDFH research group is developing two CSs related to the use of seasonal forecast of precipitation, temperature and river flow for water (ROAT service) and energy (SHYMAT service) sectors. Both services are being tested over Sierra Nevada, in Southern Spain, a Mediterranean high mountain area where the snow has a critical influence over the hydrology of the downstream areas. Under these circumstances, climate is extremely variable and seasonal forecasts show a very limited skill and performance. It is not strange as the effect of synoptic states over this region is critical and small variations in the trajectories of the storms can turn an unusually dry month into an unusually wet one. Snowfall and snowmelt simulation made by regional models is also a critical factor. This effect can be partially overcome by using long-term measurements that makes it possible to apply bias correction methods that significantly improve the skill of the forecasts. Also after the application of a physically-based hydrological model (WiMMed), some drifts in the amount of snow and timing of snowmelts could be corrected, thanks to a finer simulation of the hydrological processes at detailed scale (30 m). With all this, we can confirm that the use of seasonal forecast data 6 months in advance for the operation of reservoirs and hydroelectric power plants improves the knowledge behind management decisions compared to knowledge only based on past experiences. And it is expected to improve in the near future. The services are offered to the user as a cloud web application, where the results are kept simple and intuitive, while supported by the state-of-the-art knowledge on snow hydrology and weather forecasting.

SWE modelling for the optimisation of hydropower production in alpine catchments

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We present ten years of operational use of a distributed hydrological model (GEOtop) for the simulation of water availability in glacierized mountain catchments in North-Western Alps (Aosta Valley, Italy) devoted to the optimization of hydropower production. The activities are conducted in close contact with the hydropower company CVA that is mainly interested in the following output variables: i) maximum snow water equivalent (SWE) before the onset of the melt period and ii) the seasonal evolution of SWE between May/June and October. The study areas vary from 10 km^2 to 140 km^2, covering a wide altitudinal range from 2000 to 4150 m a.s.l., thus representing typical high mountain conditions. The modeling framework is based on the integration of field campaigns of snow depth and snow density measures, remote sensing data, and GEOtop model. Meteorological forcings from several automatic weather stations are spatially interpolated (meteoIO library) and used by the model to solve the ground surface energy balance. Modeled liquid and solid precipitation, snowmelt, and glacial melt are accounted to infer the total amount of water available in the catchment at daily time-step. To quantify the uncertainty of the simulations, (i) the modeled water volumes are compared with the total amount of water measured by the hydro-power company at the power-plant and (ii) the temporal evolution of modeled snow-covered area (SCA) is compared with observed snow-covered area derived from Sentinel2 satellite images. The temporal variability of modeling results, source of uncertainties in both modeled and validation data and the recurrent spatial patterns of errors distribution are presented and discussed.

Assessment of water resources of the Amudarya river zone of runoff formation by remote sensing methods

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The study of the regime of the rivers of the Amu Darya basin in the zone of runoff formation under the conditions of global climate change and the threat of the desiccation of the Aral Sea and the increasing frequency of natural disasters is an important research task. Gunt river basin, Tajikistan, Central Asia was selected as a test option and it belongs to the Pamir mountain system. The Gunt River belongs to the alpine rivers of glacial-snow feeding. The length of the river is 296 km, the basin area is 16,000 km^2, the average elevation of the basin is 4170 m above sea level, and the area of glaciation occupies about 4% of the total basin area. The methodologies currently used in Central Asian countries to assess water resources are based only on data obtained from a limited number of meteorological stations located in remote mountain regions with extreme weather conditions. Besides, the available information from weather stations has the character of a point data observations and has no spatial distribution. In this study, the authors used remote sensing data to spatially estimate snow cover and, accordingly, to estimate river water content during flood months. Spectroradiometer snow data (MODIS) with moderate resolution (MOD10A1 - Terra, MYD10A1 - Aqua, versions 5 and 6) have a spatial temporal resolution of 500 meters and an observation period from 2000 to the present. The disadvantage of the MODIS snow cover product is the lack of data due to cloud cover because MODIS is an optical sensor. To overcome this limitation in snow cover data, several cloud cover removal algorithms were previously developed in MODSNOW, which can be used to automatically process MODIS snow cover data, including cloud cover removal (estimation of the actual pixel coverage under a cloud cover).The obtained correlation dependences of the average monthly water discharge for the flood months with snow cover indices (SCI) showed a high tightness of the dependence (R) for the months of seasonal snowmelt and the passage of maximum water discharge: in June –0.71, in July –0.87, in August - 0.56, in September - 0.78. The results obtained make it possible to estimate the water content of the Gunt River for future months of flood based on snow cover data from MODIS images.

Session 3: Climate change, snow conditions and water supply

Changes in snow cover over Central European low mountain ranges

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Most studies on the impact of global warming on snow cover are focusing on high mountain regions. A major part of Europe is however composed of low mountain ranges, which peak at about 1500 m. Surprisingly, few snow related investigations are available from these regions, although snow cover plays an important role for runoff conditions, biodiversity and recreational purposes. In this study, we investigated the recent snow cover changes over a central European low mountain range, where the seasonal snow is particularly sensitive to temperature increase and frequently affected by rain-on-snow (ROS) events. We simulated the snow water equivalent (SWE), ROS events, evapotranspiration, and runoff for the period 1961–2016 in southwest Germany using a distributed hydrological model (TRAIN). We analyzed the intra- and inter-annual variations of the simulated hydrological variables and the synchronous climate variables (air temperature and precipitation). Trend detection indicates a significant SWE decline throughout the snow season, but principally at the high elevations. The most severe warming occurred in early spring (March) while precipitation showed a slight increase in January and February. February snowpack has displayed the most striking reductions, which is likely driven by both the highest susceptibility of snow to warming and an increased ROS occurrence in February since the early 1990s. The increased combination of high temperatures and increasing rainfall, as well as the earlier snowmelt has resulted in a runoff increase during the earlier winter, but to a decrease in March. The expected changing climate towards warmer and wetter winters will probably exacerbate winter flooding in the future.

Keywords: Snow water equivalent, snow cover, climate change, rain-on-snow events, snow modelling

Snow cover dynamics in the Pamir and Tianshan mountains and its attribution to climate change

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Snow cover is the most important water formation component in the Central Asian hydrology. The accumulation of snow in the mountains of Pamir and Tianshan during the cold period regulates the summer runoff of rivers. Due to its arid climate, water formed in the summer months is highly important for agricultural production. Moreover, water generated mainly due to snowmelt is important for the energy production of dozens of hydroelectric power plants. Thus, snow plays an important role for economic stability and is important for food security due to agricultural production. In this study, we analyzed snow cover dynamics in the Pamir and Tianshan Mountains of Central Asia. We used observed snow depth data from available stations for this study. Due to the limited number of observations, especially at high altitudes, we also used remote sensing-based snow cover data over the last 20 years to understand the snow cover dynamics and its variability due to climate change. The daily Moderate Resolutions Imaging Spectroradiometer (MODIS) snow cover data with 500-meter spatial resolution was used in this study, which was processed using the MODSNOW-Tool. The obtained results show various insights into snow cover variability in Central Asia. The obtained trends are also different according to geographic location and altitude. In most of the river basins, the significant increase in snow cover trend was observed. In the fall season, the decrease in snow cover was observed. The attribution of snow cover changes to meteorological parameters such as temperature and precipitation shows that increasing precipitation in some river basins is the reason for snow cover increase in the spring months. However, it was also found that the snow cover has a "memory effect" for which monthly attribution of meteorological parameters is not possible, but rather meteorological parameters a few months before the snow cover change observations. The obtained results are important for Central Asia and its hydrology. The changing pattern of intra-annual snow cover also shows the potential shift of the hydrological regime, which should be considered in the development strategies of water management in the future.

Widespread and accelerated decrease of mean and extreme snow depth over Europe

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Accumulated snow amounts impact society in many ways and are a key climate change indicator. It combines the competing effects of climate change-driven changes in precipitation and stronger snowmelt related to increasing temperatures. These competing effects make that the effects of a warming climate on snow depth and snow depth extremes are not straightforward. In this presentation, in situ snow depth observations are analysed from a pan-European dataset. Earlier modelling studies hypothesize that in future climates, using a strong warming scenario, contrasting responses to climate change are found between mean snowfall and extreme snowfall, with smaller changes in extreme snowfall than in mean snowfall. Here we provide observational evidence from a pan-European in situ data set that mean snow depth generally decreases stronger than extreme snow depth, and that this contrast has increased in the recent decades. Widespread decreases in maximum and mean snow depth were found over Europe, except in the coldest climates, with an average decrease of -12.2%/decade for mean snow depth and -11.4%/decade for maximum snow depth since 1951. These trends accelerated after the 1980s.This has strong implications for the availability of freshwater in spring, while extremes in snow depth, usually very disruptive to society, are decreasing at a slower pace. However, how snowmelt rates are responding to decreases in snowpack and the associated impacts on water resources are poorly understood and are subject of current studies.

Can climate models represent the snow occurrence in semiarid areas? The example of Sierra Nevada Mountain Range

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Climatic models show a decreasing trend in precipitation and an increasing trend in temperature on an annual basis for the near future in the Mediterranean regions. Huge effort has been done to correct biases in climate modelling by adjusting independently temperature and precipitation regimes to observations during the past period. However, in mountain areas, with occurrence of snow events, the capability of models to appropriately simulate the interaction of both precipitation and temperature is key since an incorrect timing between them can mismatch the amount of snow. This might not be a problem in northern latitudes, where the low temperatures during the snow season make this mismatching almost negligible. Nevertheless, in semiarid regions, where the lower temperatures during the snow season are usually in the order of zero degrees, this can constitute a significant source of error. This work presents a first analysis of the snow occurrence by climate models in a semiarid mountainous range in southern Spain: Sierra Nevada Mountains. Snow occurrence is quantified by the interaction between precipitation and temperature regimes using a simple temperature threshold model. Twelve GCMs-RCMs (Global Circulation Models – Regional Circulation Models) combinations are used and two variables computed at the annual scale: snowfall amount and number of days with snowfall within a year. The twelve models' combinations are assessed for the past period against in situ observations. The results can constitute the first approach to assess the validity of climate simulation to study snow occurrence over these areas, delimit the uncertainty of climate models and establish the foundations of a combined bias adjustment technique which jointly takes into account both precipitation and temperature regimes.

Snow precipitation trends in the Adige valley: a citizen's science dataset

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Snow is an important resource for the Alpine environment and for the economy of its valleys and it presence has a relevant impact on citizens' life. In the southern side of the Alps and at mid and lower levels snow precipitation depends often on a balance between the availability of precipitations and low temperatures. To have a detailed picture of the changes in the winter snow accumulation a capillary network of observations is necessary, with manned stations integrating more sparse automated measurement. While at mid and high elevations are present extensive institutional networks, at the lowest elevation, where reside most of the population, time series are much more fragmentary. However, at the lowest elevations is where the reduction in the chances of colder conditions has most affected snow presence in the recent decades. Therefore, there is the need of an improved ground snow monitoring. In Trentino-South Tyrol the members of an association of private citizen (Meteo Trentino-Alto Adige) has maintained a series of snow observations which spans up to 140 years in the case of the city of Rovereto, providing an interesting insight on the distribution and decadal changes in the winter snowfall at mid and low-elevation. In this contribution we analyze a dataset explore its potential for the study of snow cover in complex terrain. Data show a strong decreasing trend in yearly total snow accumulation for all considered locations the last 40 years, which decreased of about 50%. This corresponds to an increasing trend in temperature, but not in winter total precipitation, which shows no significant trends. We discuss uncertainties due different approaches in manually measuring snow and, for the last decade, we analyze more in details snowfall patterns comparing ground and remotely sensed observations. Local differences in snow accumulation are related to orographic factors, with a maximum accumulation in the mean part of the valley, near Trento, due to opposite gradients of temperature and precipitation amount along the valley.

Session 4: Climate change, snow conditions and water supply

Long-term (1900-2100) SWE and Hydrometeorological reconstructions in the French Southern Alps (Durance watershed and Mercantour Natural Parc)

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The aim of this communication is to study climate variability and change on snow water equivalent (SWE) and streamflow over the 1900-2100 period. It is based on SWE and streamflow observations, past reconstructions (1900-2018) and future GIEC scenarios (up to 2100) of some snow courses and hydrological stations situated within the French Southern Alps (Durance watershed and Mercantour Natural Parc). This has been conducted by EDF (French hydropower company) and Mercantour Natural Parc. This issue became particularly important since a decade, especially in regions where snow variability had a large impact on water resources availability, poor snow conditions in ski resorts and artificial snow production or impacts on mountainous ecosystems (fauna and flora). As a water resources manager in French mountainous regions, EDF developed and managed a large hydrometeorological network since 1950. A recent data rescue research allowed to digitize long term SWE manual measurements of a hundred of snow courses within the French Alps. EDF have been operating an automatic SWE sensors network, complementary to historical snow course network. Based on numerous SWE observations time-series and snow modelization (Garavaglia et al., 2017), continuous daily historical SWE time-series have been reconstructed within the 1950-2018 period. These reconstructions have been extended to 1900 using 20 CR (20th century reanalyses by NOAA) reanalyses (ANATEM method, Kuentz et al., 2015) and up to 2100 using GIEC Climate Change scenarios (+4.5 W/m² and + 8.5 W/m² hypotheses). In the scope of this study, Mercantour Natural Parc is particularly interested by snow scenarios in the future and its impacts on their local flora and fauna. Considering observations within Durance watershed and Mercantour region, this communication focuses on: (1) long term (1900-2018) analyses of variability and trend of hydrometeorological and snow variables (total precipitation, air temperature, snow water equivalent, snow line altitude, snow season length, streamflow regimes), (2) long term variability of snow and hydrological regime of snow dominated watersheds and (3) future trends (2020 -2100) using GIEC Climate Change scenarios. Comparing old period (1950-1984) to recent period (1984-2018), quantitative results within these regions roughly shows an increase of air temperature by 1.2 °C, an increase of snow line height by 200m, a reduction of SWE by 200 mm/year and a reduction of snow season duration by 15 days. Characterization of the increase of snow line height and SWE reduction are particularly important at a local and watershed scale. Then, this communication focuses on impacts on long-term time scales (2050, 2100). This long-term change of snow dynamics within mountainous regions both impacts (1) water resources management, (2) snow resorts and artificial snow production developments or (3) ecosystems dynamics. This study allowed to provide some local quantitative scenarios.

The impact of climate-change induced alteration of snow and glacier processes on solar-hydropower complementarity in Alpine basins

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Renewable energy installed capacity is increasing worldwide due to growing concern about greenhouse gas emissions. In mountainous areas, variable and intermittent power generation from wind and/or solar sources is often combined with hydropower in order to smooth out the total generation and, by this mean, facilitate integration of renewables into the electricity network. Although previous research work focused on the impact of climate change on the complementary between hydropower and renewables, the effects of glacier shrinkage on hydropower and subsequent complementarity has been disregarded so far. This research aims at filling this gap. Data from the upper Adige river basin (Eastern Italian Alps) are used for the analysis. The Decision Scaling approach is used to analyze the system sensitivity and vulnerability to change in precipitation, temperature and glacier volume. Results show that glacier shrinkage and climate change leads to a marked change of seasonal hydropower production. As a consequence, the complementarity between hydropower and solar PV increases in a marked way in the head basin with the largest original glacier coverage which is mostly affected by glacier shrinkage. Changes in complementarity are not significant with increasing catchment size and corresponding decrease of glacier contribution.

Snow reliability and alpine ski sport in Germany

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Snow reliability in alpine ski resorts is an issue for winter tourism and its economic efficiency. If snow coverage decreases and good conditions for snow sports shift to higher elevations, tourism industry may be threatened by economic losses. Which snow depth is sufficient for snow sports depends on various conditions, such as the kind of activity or the terrain characteristics. However, there is a general agreement that a snow depth of 30 cm would be sufficient for alpine skiing, and 50 cm would be good. An indicator for a successfully operating ski resort is the so-called 100-days rule, which states that sufficient snow conditions should prevail during 100 days of a year in the resort in question. We developed an algorithm to investigate this issue facing the travel areas with alpine skiing in Germany, hereafter shortly referred to as travel areas and defined an indicator which counts the number of days with a snow depth of at least 30 cm from November to April. An example for such a travel area is the Southern Black Forest. This indicator is computed from snow depth observations at DWD stations in the travel area of concern or nearby. Only data from stations situated at elevations between the minimum and maximum altitude of the corresponding travel area were used. Furthermore, we analysed the statistical relations between this indicator and the station elevations in larger regions in Germany, the so-called 'natural regions'. Based on the regression relations identified in natural regions with travel areas, we projected the indicator values of the stations to the mean elevation of the travel area in question. If there are several stations in one travel area, averaging weighted by elevation is performed. For all travel areas within a ski-touristic area (e.g. all travel areas within the Black Forest), the indicator is further aggregated based on the length of the ski slopes there. We first analysed snow depth data for the period from 1970/71 to 2012/13. The results were published in the Monitoring Report on the German Strategy for Adaptation to Climate Change. Only in the Alps is the 100-days rule fulfilled in most of the years. A remarkable number of years with sufficient snow reliability was also identified in the Eastern Low Mountain Range. In the other ski-touristic areas, the threshold of 100 days with a snow depth of at least 30 cm is exceeded in few years only. In this stage of aggregation, no trends could be identified for the indicator in any of the ski-touristic areas. This may be linked to the high temporal variability of the indicator. In some individual travel areas, however, there are trends towards a decline of snow reliability. We continued these investigations with data for the period from 2013/14 to 2017/18. For some of the travel areas, we found an increase in reduced snow reliability. It is intended to update the indicator in regular intervals. In addition, the underlying method will have to be revised to account for temporal changes in the statistical relations.

Snow Monitoring for Water Availability and Irrigation – contributions within H2020 Extreme Earth

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A specific presentation / poster contribution on GNSS snow monitoring using SnowSense will be given by Dr. Franziska Koch, BOKU Vienna. Due to a changing earth and a growing population, food security is one of the most challenging issues of this century. Biomass production and yield will need to be increased, but especially the risk of yield loss under the extreme environmental conditions need to be minimized. In this context the knowledge of water resources (esp. in the cryosphere) and the management of water demand – keyword irrigation - needs to be improved. Methods of Extreme Analytics regarding EO data volume (Big Data from Copernicus), new algorithms (Deep Learning application) and information transfer (modelling) are integrated within two use cases in the H2020 project (2019-2021). (http://earthanalytics.eu)Within the Food Security use case, the team of VISTA is combining existing EO technologies (Copernicus), water balance modelling and novel GNSS technologies ('SnowSense') to provide all information on the water and resources and the day by day water availability for the management and planning of irrigation measures. In Extreme Earth, the context of changing water resources and changing water demands in larger, European catchments, with significant water storage in the cryosphere, was chosen as one of two use cases to demonstrate the extreme analytics to be enhanced and developed within the project. We will present the motivation, design and development of our water availability and irrigation information pilot applications we are planned with our project partners and demo users focusing on the River Danube catchment (first phase) and the River Duero catchment (second phase). Those activities include big data processing of Sentinel-1 and Sentinel-2 using ESA Thematic Exploitation Platforms (Polar TEP and Food Security TEP), application of Deep Learning tool (e.g. for sea ice and crop type monitoring) and Linked Data application. For the SnowHydro conference, we will present the overall concept of the use case, the transition of research and development to application in technical and socioeconomic context. We will highlight the benefits of winter in-situ SWE and LWC measurements using distributed GNSS based station systems in mountainous areas (stations are in operation in Germany, Switzerland and Slovakia), in combination with EO and physical modelling (snow and runoff) in the context of catchment hydrology regarding agriculture and water supply in the lowlands in spring and summer. A specific presentation / poster contribution on GNSS snow monitoring using SnowSense will be given by Dr. Franziska Koch, BOKU Vienna. Co-authors: Dr. Markus Muerth, Dr. Heike Bach (VISTA) + relevant partners will be added.