SnowHydro 2018

Book of Abstracts

International Conference

on

Snow Hydrology

February 12-15, 2018, Heidelberg, Germany

About this publication

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Session 1: Snow and climate change

Chairpersons: Irene Brox Nilsen and Torsten Starkloff

Snow cover changes in European mountains derived from Global SnowPack time series

Zhongyang Hu and Andreas Dietz[1]

[1] German Aerospace Center (DLR), Wessling, Germany

Email: Andreas.Dietz@dlr.de

Abstract

Snow cover is an important variable for water availability, the radiation budget, glaciers, flora and fauna, and may cause natural disasters such as avalanches or floods. Within Europe especially in Norway, Sweden, and Switzerland, snow is an important source of freshwater for reservoirs and the subsequent production of electricity. Climate change is affecting the global snow cover distribution, extent, and mass, influencing all the aforementioned parameters. It is therefore important to monitor the developments and changes to be able to detect possible trends and future impacts of changing snow cover on our environment. Within the presented study we analysed the daily snow cover information provided by DLR's Global SnowPack product to identify snow cover developments in European mountains since the year 2000. The Global SnowPack is a medium resolution (500 m pixels) reprocessed time series based on the snow cover products MOD10A1/MYD10A1 derived from MODIS, where all gaps caused by cloud cover or polar darkness have been interpolated to provide a gapless time series of daily data. In Europe the analysis of the time series showed similar results for most mountainous regions, which are characterised by a tendency towards a decreasing snow cover duration. The only exception is Scotland where a tendency towards increased snow cover duration can be observed. The presentation will outline the techniques used to analyse the Global SnowPack and it will be illustrated for each mountain region within Europe, how the snow cover duration has been developing since the year 2000.

Inter-comparison of distributed models to analyze the sensitivity of snow cover to global warming on various mountain ranges

Denis Ruelland

National Center for Scientific Research (CNRS), Montpellier, France

Email: denis.ruelland@um2.fr

Abstract

This study aims to test several conceptual, distributed models by comparison with satellite imagery to simulate snow cover in various topographic and hydro-climatic mountain contexts: French Alps, Chilean Andes, Moroccan High Atlas, French and Spanish Pyrenees, and Kirghiz Tien Shan. Six daily models allowing the parsimonious representation of the processes of accumulation and ablation (melting and sublimation) are inter-compared at the scale of seven catchments from 200 to 500 km². A model calibration and validation protocol is proposed to evaluate the transferability to contrasting climate conditions over periods of 6 to 10 years depending on the basins. This protocol made it possible to demonstrate the most efficient structures to reproduce realistically the snow cover areas and the snow cover durations identified from MODIS snow-products that were previously gap-filled according to a common technique of temporal and spatial filters. The use of a seasonal melt factor is clearly shown to improve the simulations under semi-arid conditions. A multi-model and multi-parameter approach considering structural and parameterization uncertainty is then proposed to analyze the snow cover sensitivity to global warming. The analysis reveals that: (i) snow-covered areas could decrease by 80% in the Pyrenean, Moroccan and Chilean basins, by 50% in the Alpine basins and by 20% in the Kyrgyz basin, if temperature increased by 6°C; (ii) the altitudinal thresholds for mean annual snow cover durations of 10 to 40% would rise by about 275 m for each 2°C of temperature increase for all basins; (iii) tourism activity related to winter sports in the Pyrenees and the High Atlas could be jeopardized by an increase in average temperatures of around 2°C. These results are discussed in light of the remaining uncertainties regarding the spatialization of meteorological forcing, equifinality issues in the model calibration process and the quality of MODIS control data. Research perspectives are also proposed to improve simulations by accounting for additional factors (topography, cloudiness) on the ablation processes. This study is a first step towards linking the proposed approaches to hydrological models in order to study more precisely the potential impact of climate change on hydrological responses of the basins.

A retrospective analysis of snow impacts on permafrost hydrology

Hotaek Park

Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Kanagawa, Japan

Email: park@jamstec.go.jp

Abstract

Snow is an important factor influencing on the Arctic system. The snow cover/depth indicates overall the decreasing rates during the past few decades associated with climate warming, although the increase in the rates is found in some regions (i.e. eastern Siberia and northern Canada). To assess the effect of the snow on permafrost hydrological processes, a land surface model (CHANGE) was applied to the pan-Arctic terrestrial region during the period of 1979–2015. The simulated snow depth greatly contributed to the warming of permafrost temperature. Regionally, the significant warming of permafrost temperature was found in eastern Siberia where the snow depth obviously increased. Statistical analysis suggested that the warming permafrost temperature was highly correlated to the increase of winter river discharge. Warmer air temperature derived earlier snow melt with larger discharge peak in the spring, consequently providing larger and warmer river water to the Arctic Ocean that is still completely covered by sea ice. The insulation of snow cover also limited the growth of river ice during the winter. These results suggest that snow cover could play a more important role in the Arctic hydrologic system under conditions of future Arctic warming.

Diagnosing land–atmosphere coupling in a seasonally snow-covered region (South Norway)

Irene Brox Nilsen[1]; Helene B. Erlandsen[2]; Frode Stordal[2]; Chong-Yu Xu[2]; Lena M. Tallaksen[2]

[1] The Norwegian Water Resources and Energy Directorate, Oslo, Norway
[2] University of Oslo, Oslo, Norway

Email: ibni@nve.no

Abstract

South Norway has been identified as a region where warming in spring and summer could potentially be enhanced by land–atmosphere coupling. It is hypothesized that warming in South Norway is enhanced by the snow albedo feedback in spring and by the soil moisture–temperature feedback in summer. To examine this, the Weather Research and Forecasting (WRF) model coupled to Noah-MP was used for simulations from mid-May through September 2014. Because the soil moisture–temperature feedback requires dry soil moisture conditions, dry conditions were simulated by i) increasing the length of the snow-free season, and ii) introducing boundary forcing from a warm and dry summer (2006). Six model runs were performed: the first three runs differed only in their initial ground conditions (snow-poor, control and snow-rich) and used boundary forcing from the warm 2014 summer. The next three runs kept the same initial conditions as before and used boundary forcing from the warm and dry 2006 summer. Results show that the snow albedo feedback is an important driver of warming in regions with snow changes during spring. The soil moisture–temperature feedback was detected in the Oslofjord region, at least during parts of the summers 2014 and 2006. Here, the warming was enhanced through reduced evaporative cooling, due to dry soil. The effect of changing the boundary forcing to a warm and dry summer was stronger than increasing the length of the snow-free season. This study contributes to a better understanding of what causes the observed warming in cold climates.

Thermo-insulation effect of a seasonal snow-cover on permafrost soil in Bayelva, Svalbard (1998 - 2017)

Sabrina Ebenhoch[1,2,3]; Marion Maturilli[3]; Kurt Roth[4]; Bernhard Höfle[1,2]; Julia Boike[3,5]

[1] Department of Geography, Heidelberg University, Heidelberg, Germany
[2] Heidelberg Center for the Environment, Heidelberg University, Germany
[3] Alfred-Wegener-Institute for Polar and Marine Research (AWI), Potsdam, Germany
[4] Institute for Environmental Physics, Heidelberg University, Heidelberg, Germany
[5] Humboldt University, Institute for Geography, Berlin, Germany

Email: ebenhoch@iup.uni-heidelberg.de

Abstract

Bayelva is a high-arctic research site on Spitsbergen Island in the Svalbard archipelago (78.551N; 11.571E) where climate, soil and snow components are recorded since 1998 by the Alfred-Wegener-Institute. This study site is underlain by permafrost with average temperatures around -2 °C and seasonally snow-covered from October to May. The thermal insulation by the snow-pack decouples the soil temperatures from air temperature. To gain better understanding of the thermal relationships, analysis of long-term measurements of air temperature, radiation, soil temperature, and snow characteristics were examined in this study. Mean annual air temperature has increased by 0.14 °C per year for the period from 1998 to 2016 which is higher than the global average temperature change in the same period. Radiation balance trend analyses are characterized by an increase in long-wave radiation during winter months. Results of our snow characteristic studies show that the last day in the year with snow cover has been moving to earlier dates with 0.5 days per year (from 1998 to 2016), extending the snow-free season, thus resulting in more time for soil warming. This corresponds well with warming trends of all soil temperature sensors as well as the thickening of the active layer (ALT), which is estimated to have reached a depth of 2 m in 2016 for the first time. Since it is difficult to measure the exact ALT, we used the Stefan model for an estimate. To account for different magnitudes of insulation, an effective snow depth (Sdep,eff) was calculated for each year. High Sdep,eff values represent high thermo-insulation, due to early snowfall and long snow depths over 0.4 m, and can be linked to years in which re-freezing of the whole active layer took until early March of the next year. Our results support the importance of snow physical characteristics for the permafrost thermal regime, as also detailed in the Arctic Monitoring and Assessment Programme - an Arctic Council Working Group.

Warming increases spatial hydrological homogeneity: Sensitivity of fluxes in a catchment dominated by wind redistribution of snow

Adrienne Marshall[1]; Timothy Link[1]; John Abatzoglou[1]; Gerald Flerchinger[2]; Danny Marks[2]; Linda Tedrow[3]

[1] University of Idaho, Moscow, United States
[2] USDA ARS, United States
[3] Idaho Geological Survey, Moscow, United States

Email: tlink@uidaho.edu

Abstract

Drifting snow contributes to the presence of hydrologic refugia and spatial heterogeneity in complex terrain, but may be reduced by a transition from snow to rain. In this study, we assessed the climate sensitivity of a drift-subsidized refugium in a small, semi-arid mountainous catchment in the snow-to-rain transition zone. We conducted climate experiments using a previously validated, physically based hydrological model with 30 years of historic data to assess the relative temperature sensitivity of a suite of hydrologic metrics in three different landscape units, the potential for increased precipitation to mitigate the effects of warming, the potential for a shift from energy- to-water limitation, and changes in interannual variability. With warming of 3.5 °C, maximum snow water equivalent (SWE) in the three units decreased by 58-68% and total water available for streamflow decreased by 72%. In the drift-subsidized site, warming resulted in a shift from a regime in which 16 of 30 water years were water-limited to one in which 29 of 30 water years were water-limited. Warming also resulted in altered interannual variability of hydrologic variables; these changes varied between landscape units and hydrologic metrics. The drift-subsidized unit was generally more sensitive to warming than the surrounding landscape, with reduced potential for the effects of warming to be offset by increased precipitation. Despite this, the drift-subsidized unit retained its status as a relatively mesic site with greater maximum SWE than the surrounding landscape. These changes suggest an increase in hydrologic homogeneity across the landscape and dramatic changes in drift-subsidized refugia.

Session 2: Recent advances in experimental snow research and new measurement techniques

Chairpersons: Ole Rössler and Franziska Koch

Operational Snow Measurements with Georadar – A Case Study from Överuman, Sweden

Wolf-Dietrich Marchand[1]; Björn Norell[2]

[1] Sweco Norge AS, Trondheim, Norway
[2] Vattenreguleringsföretagen, Östersund, Sweden

Email: wolf.marchand@sweco.no

Abstract

A method for designing effective snow measurement systems for hydropower plants has been applied to several catchments in Norway and Sweden over the past 15 years. The method establishes representative snow measurement survey lines which reflect the physical characteristics for the entire catchment. The method is based on GIS analysis of the following seven terrain parameters: elevation, slope, aspect, curvature, location (x- and y coordinates), and vegetation. Snow measurements are performed by towing a “snow radar” (ground penetrating radar) behind a snowmobile along the determined snow survey lines. Measurements of the two-way travel time (TWT) of the radar signal are then used to calculate snow depth. Density measurements are used to convert snow depth to snow water equivalent (SWE).

The presented study is based on 74 km of snow courses measured during March 2017 in the Swedish basin Överuman. Överuman is located in the upper part of a hydropower system along the Umeälven River. The mean snow depth in the catchment was approximately 179 cm, with values ranging from 0 to 923 cm. Based on measured SWE and measured or calculated runoff, a water balance study was performed after the end of the snow melting season. The snow data were also used for updating the model state in the hydrological Hydrologiska Byråns Vattenbalansavdelning (HBV) model. Incorporating snow measurements resulted in a better match between observed and simulated (modelled) runoff. This provides a better estimation of hydropower production and helps to avoid flood spill.

Cosmic-ray neutron sensing as a new method for monitoring snow dynamics in a large footprint

Sascha Oswald[1]; Paul Schattan; Gabriele Baroni; Till Francke; Christine Fey; Johannes Schöber; Matthias Huttenlau; Stefan Achleitner

[1] University of Potsdam, Potsdam, Germany

Email: sascha.oswald@uni-potsdam.de

Abstract

The sensitivity of neutrons to water, also in form of snow, is well known and has been made use of in buried probes for soil moisture and snow in the past already. However, it can also be applied as a non-invasive above-ground method, based on the neutrons produced by cosmic-rays in the atmosphere and detecting them after interaction with water at the land-surface. Recently it could be shown that this principle can be exploited to quantify the water equivalent in snow (SWE) as a mean value averaged over an area of several hectars. We have demonstrated in a pilot study in the Austrian Alps during more than two snow seasons that for medium to high snow depths the SWE detected by Cosmic-ray Neutron Sensing is representative for this footprint. For achieving that we have combined several measurement techniques with different spatial and temporal characteristics. Measurements included (i) continuous point-scale measurements; (ii) campaigns during the snow accumulation and melting season (terrestrial laser scanning and snow pits) and (iii) continuous above-ground Cosmic-ray Neutron Sensing. While continuous point-scale SWE data largely overestimated the snowpack, SWE data based on Cosmic-ray Neutron Sensing represented values derived from terrestrial laser scanning measurements quite well. We will discuss implications of our results on the future application of Cosmic-ray Neutron Sensing, its possible improvements and its basic limitations. Data provided by this method could be valuable in the future for snow water resources assessment, snowpack modelling and hydrological simulations, and as ground-truthing for satellite based remote sensing.

Snow monitoring with a novel GNSS approach at a high-alpine station

Franziska Koch[1]; Patrick Henkel[2]; Florian Appel[3]; Heike Bach[3]; Monika Prasch[1]; Schmid Lino[4]; Jürg Schweizer[4]; Wolfram Mauser[1]

[1] Ludwig-Maximilian-University Munich, Munich, Germany
[2] ANavS GmbH, Munich, Germany
[3] VISTA Remote Sensing GmbH, Munich, Germany
[4] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

Email: f.koch@iggf.geo.uni-muenchen.de

Abstract

For numerous hydrological applications, continuous information on the snow water equivalent (SWE) of a snowpack and the temporal evaluation of SWE is highly relevant. Moreover, information on the start of snow melt and its melt-freeze cycles are very valuable, e.g. for predictions on runoff and hydropower generation. In situ measured snow properties are essential for the validation of remote sensing data as well as for model inputs and improvements. However, until now, continuous measurements are either scarce, expensive, time consuming or lack temporal or spatial resolution, especially in mountainous and remote regions. With our novel approach, we derive SWE and the liquid water content (LWC) in snow based on the freely available signals of the Global Navigation Satellite System (GNSS). Two static low-cost Global Positioning System (GPS) receivers and antennas were installed at the high-alpine SLF test site Weissfluhjoch at 2540 m a.s.l. in Switzerland. The setup is running since autumn 2012, generating a time series of over five entire winter seasons. One antenna is placed on the ground below the snowpack and the other antenna on a pole above the snowpack. On one hand, we process GPS L1-band carrier phases measurements to directly calculate SWE for dry-snow conditions. Before the first snow fall, the baseline between the two antennas is 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 are eliminated and atmospheric errors are mitigated. As soon as snow accumulates on top of the lower antenna on the ground, the GNSS signals are delayed compared to signals, which travel by the speed of light in air. This effect is tracked via carrier phase residuals, which express the SWE projected into the direction of incidence. On the other hand, we use the carrier-to-noise power density ratio (C/N0) as signal strength information to derive LWC. Combining carrier phases and signal strength information we are also able to determine SWE for wet-snow conditions. We validated the GNSS derived SWE measurements with data from a snow pillow and manual snow pits during the seasonal evolution of the high-alpine snowpack. All reference measurements for validation were taken at the same test site in close location to the GNSS sensors. The correlation regarding SWE between our GNSS system and the conventional measurements is very good, especially under dry-snow conditions (RMSE: 11-23 mm w.e.). Moreover, the GNSS derived LWC agrees very well with LWC data recorded simultaneously by an upward-looking ground penetrating radar (RMSE: 4-7 pp by volume). In general, this novel method can be applied to a dense network of low-cost GNSS receivers to improve the spatial information on snow. This is currently demonstrated in the ESA IAP Demo project SnowSense at several locations in Canada and Europe.

Innovative snow melt and run-off sensor

Christoph Sommer

Sommer GmbH, Koblach, Austria

Email: christoph.sommer@sommer.at

Abstract

The innovative snow melt and run-off sensor SMA determines the contants of ice and liquid water in the snow pack by measurnig complex impedances along flat ribbon sensors at different frequencies. Based on a mixing model the volume contents are estimated. Liquid water content is a unique parameter containing relevant information for the prediction of the water run-off during snowmelt. A significant increase of the liquid water content is the crucial indication for the beginning of the run-off.

Understanding snow processes in mountainous region: Observation system and integrated model

Hongyi Li

Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

Email: lihongyi@lzb.ac.cn

Abstract

Snow processes are not well understood in high mountainous region because of precisely data are not available, especially precipitation are underestimated in high altitude. Intensive observations and model simulation are urgently necessary in these regions. An integrated snow observation system are set in the Qilian Mountains of China, which is located in the northeastern escarpment of Tibetan Plateau. The system locates at Yakou (4146m), focuses on the snow mass and energy fluxes at grid scale. These observation variables include snow water equivalent by a γ-ray observation system, blowing snow flux by FlowCapt instrument, evaporation and sublimation on the snow surface by Eddy Covariance (EC) system, snow density and moisture by Snow Pack Analyzer (SPA). Snow coverage is continuously monitored by a digital camera. A physically based snow model is also developed to simulate the snow processes and compare the results with observation. Based on the observation and simulation results, we indicates that the snowfall is seriously underestimated in high altitude, while blowing snow events influence the snow accumulation processes. One-dimension snow model is not enough to simulate the snow processes in high wind speed conditions. The role of wind field should be paid more attentions, especially in high mountainous region.

The quantification of snow meltwater in a snow-dominated catchment based on a spatially distributed isotope sampling network

Andrea Rücker; Jana von Freyberg; Massimiliano Zappa; Stefan Boss

WSL Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland

Email: andrea.ruecker@wsl.ch

Abstract

Snow cover is an important fresh water resource as its meltwater contributes significant volumes to mountainous streams and their valleys downstream. However, the predicted effects of the temperature rise will likely change the water storage volumes and the runoff behaviour in snow-dominated catchments. Therefore, in order to assure water availability, improved predictions are needed to adapt the water management in the future. Hence, a detailed understanding of the hydrological processes is crucial to obtain robust predictions of river streamflow. This in turn requires fingerprinting source areas of streamflow, tracing water flow pathways, and measuring timescales of catchment storage, using tracers such as stable water isotopes (18O, 2H). For reducing the uncertainties of runoff predictions, we aim to use stable water isotopes to optimize the parameter calibration of the hydrological model PREVAH (Precipitation Runoff and Evapotranspiration HRU- Hydrological Response Unit). For this, we have established an isotope sampling network in the Alptal, a snowmelt-dominated catchment (46.4 km2) in Central-Switzerland, as part of the SREP-Drought project (Snow Resources and the Early Prediction of hydrological DROUGHT in mountainous streams). Our regular sampling network collects samples from different runoff components (snowpack, precipitation, discharge). Additionally, an optimized snowmelt lysimeter samples cumulative daily snowmelt and records snowmelt rates at 1-min resolution at three locations different in vegetation (grassland, forested) and elevation (1180 m.a.s.l, 1200 m.a.s.l, 1400 m.a.s.l).

We will present isotope time series from our regular sampling network, as well as results from our snowmelt lysimeter sites from the winter season 2016/17. Initial results from the modelled snowmelt rates will be compared with the recorded snowmelt rates from our three sampling locations. Our dataset will allow for detailed hydrograph separation based on stable water isotopes and geochemical components, which we use to identify source areas, to quantify snowmelt contributions to streamflow and optimize the parameter calibration for runoff prediction.

Snow process monitoring in montane forests with a digital camera network

Chunyu Dong[1]; Lucas Menzel[2]

[1] University of California, Los Angeles, United States
[2] Heidelberg University, Heidelberg, Germany

Email: chunyudong@ucla.edu

Abstract

A camera network has been applied to monitor snow height and snow interception with high temporal resolution in montane forest environments (800-1200 m a.s.l.) in southwestern Germany. A typical feature of this region is the high temporal variability of weather conditions, with frequent snow accumulation and ablation processes and recurrent snow interception on conifers. We developed a semi-automatic procedure to interpret snow depths from the digital images, which shows high consistency with manual readings and station-based measurements. To extract the snow canopy interception dynamics from the pictures, six binary classification methods are compared. MaxEntropy classifier shows obviously better performance than the others in various illumination conditions, and it is thus selected for a qualitative analysis of snow interception. The snow accumulation and ablation processes on the ground as well as the snow loading and unloading in forest canopies are investigated based on the snow parameters derived from the time-lapse photography monitoring. Besides, the influences of meteorological conditions, forest cover and elevation on snow processes are considered. Further, our investigations serve to improve the snow and interception module of a hydrological model. We found that time-lapse photography proves to be an effective and low-cost approach to collect useful snow-related information which supports our understanding of snow processes and the further development of hydrological models. We will present selected results from our investigations over two consecutive winters.

Using a rain-on-snow simulator to study the influence of snow properties on discharge generation

Ole Rössler[1]; Till Zaugg; Sabine Probst; Rolf Weingartner[1]

[1] University of Bern, Bern, Switzerland

Email: ole.roessler@giub.unibe.ch

Abstract

During rain-on-snow events both, the dampening and the intensifying effect of snow in terms of runoff generation is known: Snow can temporally store the rainfall water, it can concentrate the runoff via preferential flow-paths, and serve as a source for additional melt water. Recently, several experimental as well as modelling studies have been accomplished to improve our understanding under which conditions which of the different processes prevails or dominates.

During the past winters a new rain-on-snow simulator was developed that allows to irrigate natural snow packs with various rainfall intensifies while monitoring runoff, snow temperature, and weight of the snow pack. 51 experiments covering a range of rainfall intensities, snow pack heights, and snow conditions were conducted at the First station 2167 m above Grindelwald, Switzerland, in order to gain new data and knowledge about the role of snow properties for runoff generation.

Based on PLS regression analyses we could confirm and emphasize the crucial role of snow moisture prior to the event: the moister a snow pack is, the more runoff is generated, the higher the runoff coefficient, and the faster the runoff peak is reached; the maximum retention capacity was estimated to be ~4 vol-%, independent from the different snow properties; the highest runoff was found for old and saturated snow packs, while the highest runoff intensity could not be assigned to one snow type. The rather disappointing outcome of these series of experiments that only common knowledge was reproduced gives also confidence in the validity of the results produced by this rain-on-snow simulator. Future experiments might hopefully reveal new insights to improve our understanding on rain-on-snow processes and ultimately increase the quality of snow-hydrological forecasts.

Session 3: Advances in snow hydrological modelling and assimilation of snow data for hydrological modelling in cold regions

Chairpersons: Tobias Jonas and Timothy Link

Introduction of a SWE-SCA hysteresis in a degree-day snow model for rainfall-runoff modelling

Philippe Riboust[1,2]; Guillaume Thirel[1]; Nicolas Le Moine[2]; Pierre Ribstein[2]

[1] National Research Institute of Science and Technology for Environment and Agriculture (Irstea), Antony, France
[2] University of Sorbonne, Paris, France

Email: guillaume.thirel@irstea.fr

Abstract

Degree-day snow models have the advantage of requiring few data for running and calibration, which is of the utmost importance for real-time hydrological forecasting or assessment of the impact of climate change on snow-driven catchments hydrological regimes.

The CemaNeige model is a daily 2-parameter degree-day model that proved to be very efficient for discharge simulation when run together with a daily rainfall-runoff model (usually the GR4J model). In this work, we tested several ways of representing in a more realistic way the snowpack, based on the integration of SWE-SCA hysteresis. These SWE-SCA relationships aim at describing the heterogeneity of snow patterns both in space and time in the catchments.

With this improved model, we showed that it is possible to make use of spatial satellite MODIS SCA data to improve the snow representation without deteriorating the discharge. The sensitivity of the relative weights between snow-based and discharge-based numerical criteria was assessed. Robustness of the model (i.e. its ability to be applied on independent periods and catchments) was improved.

Realism versus simplicity in the snow routine of the HBV model

Marc Girons Lopez; Marc Vis; Jan Seibert

University of Zurich, Zurich, Switzerland

Email: marcgirons.lopez@geo.uzh.ch

Abstract

The HBV hydrological model is still widely used, partly because of its simplicity. Depicting catchment hydrology in a simple way reduces data requirements and minimises model uncertainty. However, the representation of some processes might benefit from increased model complexity. This is, for instance, the case of the snow routine in the HBV-light model version. This version uses a single temperature threshold parameter for precipitation phase discrimination and a simple degree-day method for quantifying snowmelt and refreezing processes. Nevertheless, recent research has shown that hydrological models using a more realistic representation of snow processes may be more successful in estimating runoff.

We explore and test different alternatives to the design of the snow routine of HBV-light such as considering a gradual transition between snowfall and rainfall, or implementing a seasonally variable degree-day factor. Furthermore, we explore the implementation of combination approaches by using radiation data, which has recently become available as a gridded data product in Switzerland.

We evaluate the usefulness of these modifications to the snow routine by balancing the realism in the representation of important hydrological processes in alpine and other snow-covered areas and preservation of the characteristic simplicity of the HBV model.

Influence of model spatial resolution on snow and hydrological processes at high latitudes

Jan Magnusson[1]; Stephanie Eisner; Shaochun Huang; Stein Beldring

[1] Norwegian Water Resources and Energy Directorate, Oslo, Norway

Email: jmg@nve.no

Abstract

Snow and hydrological models are useful tools for various assessments, such as judging flood risks and projecting climate change impacts. Typically, the models are run at different spatial scales depending on the study region; for small catchments often at very high resolution (grid cell sizes less than 1 by 1km) to global assessments at much coarse resolution (cell sizes of up to 50 by 50km). However, snow and hydrological models commonly include non-linear equations, and therefore the aggregation of the model inputs and land use characteristics from finer to coarser resolutions can affect the model results and predictions. In this study, we evaluate this effect for different locations throughout mainland Norway using the physically based Variable Infiltration Capacity (VIC) model. Previous studies have shown that simulations by this model for regions with climate different from our study region are highly sensitive to variations in spatial resolutions. However, for the colder and wetter climate of Norway, our simulations indicate that the model behaves linearly for most of the study period, and therefore shows low sensitivity to changes in spatial resolution.

Assimilation of Snow Observations in a Distributed Hydrological Model for the Mountainous Upper Euphrates Basin

Aynur Sensoy[1]; Bulut Akkol; Albrecht Weerts; Arda Sorman

[1]Anadolu University, Eskişehir, Turkey

Email: aynur.sensoy@gmail.com

Abstract

Snow accumulation and melting play an essential role within the hydrological cycle and they can have a major impact on water resources and the environment essentially in snow-dominated watersheds. Therefore, analyzing and forecasting snowmelt is important for hydrological purposes as well as for weather prediction and climatic models.

Snow observations are necessary for hydrological and meteorological forecast models for calibration, validation and updating. Furthermore, in-situ snow observations are also necessary for developing and validating remote sensing products. On the other hand, Data Assimilation (DA) is a very important process in hydrological modelling due to its ability to correct the model estimates of the snow state by using observations. After a proper definition of accurate quantification of errors in models and measurement system, snow data assimilation process achieves relatively consistent results especially related with snow states in hydrological models.

Wflow as a part of the Deltares Open-Streams project is a conceptual, continuous, daily and distributed model and is based on the HBV-96 model. The model is particularly useful for catchments where snowfall and snowmelt are dominant factors. The implemented assimilation technique is the Ensemble Kalman Filter (EnKF) capable of modifying the variables/states like Snow Water Equivalent (SWE) which is the most important variable with regard to runoff volumes in snow dominated basins. Data assimilation in snow hydrological models is a relatively recent advance, but one which has been enthusiastically taken up with various approaches being used. Therefore, one of the objectives of this study is the implementation of a distributed hydrologic model in combination with EnKF and assimilating SWE using in situ and satellite data for a mountainous headwater basin of Euphrates River. Data assimilation is performed using EnKF with 32 ensembles on the fully-distributed Wflow model forced with inputs of meteorological data. Four identical models were updated with no observations, observations of discharge, observations of snow water equivalent (SWE) and the latter two respectively. The performance of the fully-distributed model is yielding NSE of 0.72 for 2002-2012 water years and assimilating discharge observations boosts the NSE value to 0.85 for discharge forecasting and brings SWE and snow cover area forecasts closer to the observed in-situ and satellite snow values.

Analysis of Snow Covered Area and Snow Cover Duration in an Alpine region: insights from a distribution-function approach to snowmelt modelling

Nicola Di Marco[1]; Maurizio Righetti[1]; Mattia Zaramella[2];
Claudia Notarnicola[3]; Marco Borga[2]

[1] Free University of Bozen-Bolzano, Bolzano, Italy
[2] University of Padua, Padua, Italy
[3] EURAC Research, Bolzano, Italy

Email: nicola.dimarco@natec.unibz.it

Abstract

This work describes the inter-comparison of modelled and MODIS-derived snow cover area and snow cover duration over 5-year (from 2012 to 2016) for the Adige river basin closed at Ponte Adige (2719 Km2) in the western portion of South Tyrol (Italy). The snow accumulation and melt model is based on an extended temperature-index method which includes potential clear sky direct solar radiation at the surface in an empirical way. The snow model is integrated within the ICHYMOD basin-scale, semi-distributed hydrological model. The snow melt method is based on using a combined energy index, integrating altitude and potential clear sky direct solar radiation, as an index of snowmelt similarity and accounts for the temporal variation of the radiation distribution over the basin. With this method, pixels with similar energy index are identified and grouped together in energy index classes. The snowpack modelling is carried out for each energy index class, hence ensuring significant computational efficiency. The system is particularly suitable for the analysis of snow-related processes, allowing simulation of temporal and spatial evolution of the snow cover and snow duration with a relatively low computational effort, and providing runoff simulation at selected basin outlets.

The MODIS daily snow products are first compared with in situ snow depth (SD) and snow water equivalent (SWE) measurements. Then, we compare daily ICHYMOD snow cover simulations and MODIS snow distribution maps at 250 m resolution by using efficiency indexes such as False Alarm Ratio (FAR), Probability of Detection (POD) and CSI (Critical Success Index). The inter-comparison is carried out by aggregating the efficiency index either in time or in space, thus allowing appreciation of the temporal and spatial distribution of the discrepancies between model results ad MODIS products. The inter-comparison is integrated with the analysis of the runoff simulation efficiency via comparison with observed discharges at multiple streamflow stations within the study region. The analysis is summarized in terms of: i) sensitivity analysis of the snow accumulation and melt model parameters, showing the impact of the altitudinal distribution of solid precipitation; ii) impact of specific land uses, such as forest land use, on MODIS-model inter-comparison; iii) impact of snow-related errors on runoff simulations at various spatial and temporal scales.

Treatment of forcing data uncertainty in snowmelt modelling by using DREAM Algorithm

Zuhal Akyurek[1]; Faisal Baig

[1] Middle East Technical University, Ankara, Turkey

Email: zakyurek@metu.edu.tr

Abstract

Hydrologic models often contain parameters that cannot be measured directly but which can only be inferred by a trial-and-error (calibration) process that adjusts the parameter values to closely match the input-output behavior of the model to the real system it represents. Forcing data uncertainty is considered as one of the key source for streamflow prediction uncertainty and therefore should be treated explicitly. In this study, we utilized Differential Evolution Adaptive Metropolis (DREAM) algorithm for the assessment of precipitation and evapotranspiration (ET) data uncertainty besides the parameter uncertainty of a conceptual snowmelt model, namely NAM, which uses the degree day method in snowmelt modelling. DREAM uses Bayesian inference to solve posterior sampling distributions in complex and high dimensional problems. Two basins having different size and soil characteristics have been used in the modelling. One of the basins having 28.4 km2 is located in the northern part of Turkey, whereas the other basin has 2379 km2 area and located in the south part of the country. Both basins' mean elevation is around 1700 m. The small basin is covered with broadleaf forest and the soil is brown soil having lots of organic material in it. The large basin is covered with agricultural areas and sparse natural vegetation. Calibration of the model along with the proper treatment of forcing data uncertainty provided reasonable prediction uncertainty bounds and well defined posterior distribution of model parameters. For both of the basins, Nash Sutcliffe efficiency improved to above 0.8 after explicit treatment of forcing data error while for classical calibration it was never greater than 0.6. Similarly, for the validation period, it changed from 0.45 to 0.77. The storm multipliers for two basins is obtained as 1.1 but the ET multipliers show variations because of different climatic conditions of the basins. Although the conceptual model has been used, the calibrated model parameters are discussed in terms of their physical meanings.

A comparative study of snowmelt modelling approaches in the Moroccan High Atlas Mountains

Hafsa Bouamri[1]; Christophe Kinnard[2]; Abdelghani Boudhar[1];
Hamza Ouatiki[1]; Simon Gascoin[3]

[1] Sultan Moulay Slimane University, Béni-Mellal, Morocco
[2] University of Québec à Trois-Rivières, Trois-Rivières, Canada
[3] CESBIO, University of Toulouse, Toulouse, France

Email: h.bouamri@usms.ma

Abstract

Solid precipitations in high mountain watersheds significantly control the hydrological regime of arid and semi-arid regions around the world, and are thus of particular importance for water resources. In the Moroccan High Atlas range, considered as a water tower for downstream lower plains, understanding and modelling snow processes remains challenging due to scarce in situ measurements. This study analyses the performance of four approaches with increasing complexity to simulate snowmelt at the station scale. The models tested are: (1) a classical temperature-index model (TI); (2) a temperature index model which includes the potential clear sky direct radiation (HTI); (3) an enhanced temperature-index including the incoming solar radiation (ETI-A) and (4) the same model but which further includes the snow albedo (ETI-B). All models were subjected to calibration using snow water equivalent (SWE) observations during the 2009-2010 season, with high accuracy ($0.94<NSE<0.98$). The snowmelt simulation results over validation seasons show an acceptable performance of all tested models ($0.63<NSE<0.71$). However, the ETI-A and ETI-B models, which include the shortwave radiation and albedo, performed best, despite a consistent overestimation of the SWE.

Keywords: snowmelt; temperature index model; enhanced degree-day models; semi-arid climate; High Atlas; Morocco

Measurement based evaluation of different snow models in WaSiM for a small subalpine catchment

Matthias Kopp; Jakob Garvelmann[1]; Markus Disse[2]

[1] IMK-IFU, Institute of Meteorology and Climate Research, Garmisch-Partenkirchen, Germany
[2] Technical University of Munich, Munich, Germany

Email: matthias.kopp@tum.de

Abstract

The variety of influencing parameters for the processes of the snow accumulation and the snow ablation, like the present canopy cover, the altitude, the aspect or the wind redistribution result in a strongly heterogeneous distribution of the snow height and thereby of the snow water equivalent (SWE) in subalpine regions (e.g.: Elder et al., 1991, Jost et al., 2007). The decisive distinction of subalpine from alpine regions is the occurrence of multiple snow accumulation and snow ablation periods including the repeated complete degradation of the snow cover during the winter. This makes the modeling of the snow cover in subalpine regions a challenging task.

For the 1-D Simulation of snow cover, as well as for the utilization of 2-D snow models, the modeling of the snowmelt process by the application of the energy balance of the snow layer is a long-since approved method (e.g.: Strasser et al., 2010, Rutter et al., 2009, Liston and Elder, 2006). Recently complex energy balance methods also found their way into physically-based, hydrological models. At the moment, the existing, already very detailed modeling methods for the mere snow cover simulation are being implemented into spatially distributed rainfall - runoff models in order refine the snow melt simulation within these models.

Beside the long established snow melt models like the T-Index method and the T-Wind-Index method WaSiM already features an (extended) energy balance method (Warscher, 2014) for the calculation of the snow melt. Within the framework of this contribution a comparative overview of the performance of the different WaSiM snow models for modeling snow cover in subalpine regions will be presented. Therefore the results of the application of different snow models are compared to measurements carried out in the Dreisäulerbach catchment in the Bavarian Alps, where the chair of Hydrology and River Basin Management of the TU Munich and the Institute of Meteorology and Climate Research – Atmospheric Environmental Research of the Karlsruhe Institute of Technology have installed a measurement network in order to capture the relevant meteorological parameters as well as unsteady snow processes and the spatial distribution of snow heights and the SWE within subalpine regions.

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Trend of Degree-Day Factors in response to the Hydro-Climatological and Physiographic Parameters

Muhammad Fraz Ismail[1]; Markus Disse[1]; Wolfgang Bogacki[2]

[1] Technical University of Munich, Munich, Germany
[2] University of Applied Sciences Koblenz, Koblenz, Germany

Email: ismail@hs-koblenz.de

Abstract

Seasonal snow and glacier melt is a pivotal fresh water resource for Pakistan whose agrarian economy is vastly on dependent this seasonal water availability. Pakistan has been termed as a water stressed country because of the drastic increase in the population and mismanagement of available water resources. In this context, the snow and glacier melt runoff modelling has a prime importance for this region not only because of the availability of vast snow and glacier fields but also this region has been designated as a severely affected region due to climate change.
In view of the topographic variability and sparse measuring network density in the region simple temperature-index models have proved to be an adequate approach for modelling the snow and glacier melt. The key parameter of these models is the so-called Degree-Day Factor (DDF), which describes the relationship between the mean daily temperature and the resulting snow melt. Although the DDF is the essential model parameter of temperature-index models, there are few physical measurements for this parameter especially in the Himalayan region. Mostly, the DDF is calibrated as a model parameter on the observed discharges. Recent research using the Snowmelt Runoff Model (SRM) for calibrating the DDFs show that the DDF vary with elevation and time as the snow melt season progresses. The rapid increase of the DDFs at higher elevations in contrast to lower elevation zones in a short interval of time during the snowmelt season emphasizes a strong dependency of DDFs on the geodetic elevation. In order to investigate the dynamics of the DDFs in more detail, Koblenz University of Applied Science in collaboration with the Technical University Munich has set up a snow measurement station at the Brunnenkopfhütte (1602m asl) in the Ammergebirge catchment from winter 2016/17 and another station is planned to be installed in Deosai (> 4000m asl) in the Upper Indus Basin of Pakistan in the Summer of 2018. In addition to measuring the meteorological data, the snowpack density is determined, in particular, using a Snow Scale Ground (SSG). Furthermore, with an installed snowpack analyzer (SPA), snow, ice and water content can be continuously measured in the snow pack. Last year's measurements reveal that the snow starts to pile up in early December and the maximum of 108 cm depth and 318 kg/m2 weight of snow pack have been achieved till early March. The minimum temperature recorded during this time span was -18°C. The snowmelt started in late March and it took two weeks for snow to completely melt. First results from this measurement campaign show that the computed DDF from variation of snowpack weight ranges from 0.6 to 6.3 mm°C-1 day-1. In the poster the formation of the research project, the chosen measurement arrangement and the data obtained concerning the influence of different parameters on the development of the DDFs are presented.

A comparison study of sequential ensemble-based schemes for multivariate assimilation of snow data at different Alpine sites

Gaia Piazzi[1]; Guillaume Thirel[2]; Lorenzo Campo[1]; Simone Gabellani[1]

[1] CIMA Research Foundation, Savona, Italy
[2] Hydrosystems and Bioprocesses Research Unit (HBAN), Irstea, Antony, France

Email: gaia.piazzi@cimafoundation.org

Abstract

Because snow melt-water supplies a significant component of the annual water budget in many regions, the knowledge of snowpack dynamics is of critical importance to several real-time applications such as agricultural production, water resource management, flood prevention, and hydropower generation. With the aim of improving the hydrological predictions in snow-dominated areas, an increasing interest focuses on the combined used of different sources of information by assimilating observed data (i.e. ground-based measurements and remotely sensed observations) within models. Several data assimilation (DA) techniques with different degrees of complexity have been developed and are currently used for operational purposes. Generally, the research community agrees on the superior performance of the multivariate DA with respect to the univariate one.

This study intends to assess the feasibility of a multivariate DA scheme for snow modelling through two of the most widely used sequential ensemble-based DA techniques, namely the Ensemble Kalman Filter (EnKF) and the Particle Filter (PF). A dual purpose firstly aims at identifying and overcoming the most constraining limitations in implementing multivariate DA schemes within a snow module. Secondly, the goal is to analyze the main differences in the effectiveness of the two selected DA techniques in consistently updating the snowpack states, in order to assess their suitability to be operationally effective for real-time hydrological applications.

The modelling system, called SMASH (Snow Multidata Assimilation System for Hydrology), consists of a newly developed multilayer snow energy-balance model coupled with a multivariate DA scheme. The system is tested at three Alpine sites: Torgnon (Italy), Col de Porte (France) and Weissfluhjoch (Switzerland). Both DA configurations are analyzed in order to assess their performances in assimilating snow-related in-situ measurements and the resulting impact on snow model predictions, under changing local conditions.

A comparative analysis between the selected DA techniques has allowed to better identify their main weaknesses and strengths. The two methodologies have proved to be suitable for being implemented within a multivariable DA scheme, since they allow to take into account different sources of uncertainty. Generally, the PF technique allows to better handle the model nonlinearities. Even though the EnKF updating terms are generally larger than those of the PF procedure, the effects of the PF updating on the ensemble states last longer respect to the EnKF. Moreover, unlike the EnKF, the PF technique maintains the internal physical consistency of each ensemble member.

An accurate simulation of liquid water flow to improve firn modelling

Vincent Verjans; Amber Leeson; Keith Beven

Lancaster University, Lancaster, United Kingdom

Email: v.verjans@lancaster.ac.uk

Abstract

For the Greenland ice sheet, runoff of liquid water has become the dominant factor of mass loss, however, the link between meltwater production and meltwater runoff remains unclear. Some (322-1289 Gt for the Greenland ice sheet) melt water can be retained in the firn layer through long term storage in the liquid phase or by refreezing if the firn pack is cold. Liquid water in the firn layer can potentially have a big impact on its properties, for example the firn densification rate, temperature profile or grain size evolution. Densification is particularly affected by refreezing of vertically transported liquid water, temperature distribution by any associated heat transport plus latent heat released through refreezing, and grain size is affected by wet snow metamorphism. As both the frequency and the intensity of melting and rain-on-snow events are expected to increase in the coming years, it is important that we are able to model these impacts in order to predict future Greenland ice sheet change with greater fidelity.

Vertical water transport through surface layers in a snowpack is achieved by homogeneous (matrix) flow and rapid flow through discrete ‘pipes’ (preferential flow). Liquid water flow in this manner has been documented extensively in field observations, but accurately representing liquid water flow in firn and snow models remains challenging. This is largely due to uncertainty in our physical understanding of key processes such as the distribution between matrix and preferential flow, the velocity at which water percolates downwards, the depth that liquid water can reach and the principles underlying the formation of preferential flow pathways. These processes play a crucial role in rapidly transporting water from the surface into deep, potentially subfreezing, layers and can affect feedbacks within the system e.g. on the structure of the firn. Therefore, it is important that such processes are considered in models of firn evolution.

In my research project, I will address this by developing an improved model of liquid water transport in firn compatible with the existing Community Firn Model. Using this model, I will determine the degree to which firn densification is sensitive to liquid water flow. Particular emphasis will be placed on differentiating matrix and preferential flows and their respective impacts. Ultimately, this work will help to reduce inherent uncertainties associated with liquid water flow in firn evolution models and their predictions.

A machine learning approach to exploit snow remote sensing data for run-off prediction

Mattia Callegari; Ludovica De Gregorio; Felix Greifeneder; Carlo Marin; Marcello Petitta; Alberto Troccoli; Marc Zebisch; Claudia Notarnicola

EURAC Research, Bolzano, Italy

Email: mattia.callegari@eurac.edu

Abstract

It is recognized that in Alpine areas summer flows may be controlled by the winter accumulation of snow in the catchments, even in the presence of trends of reduced precipitation (Bartolini et al., 2009). Snow contribution, is thus increasingly included in hydrologic models applied to mountain areas. An alternative to water balance models for run-off prediction is given by models based on statistical relationships between time series of a target (e.g., monthly water discharge) and predictors. Among the predictors, the snow cover area (SCA) extracted from remote sensing optical images can provide a relevant information. In Callegari et al., 2015, SCA time series extracted from MODIS data have been successfully employed as input feature in a machine learning run-off prediction architecture.

One of the main advantages of remote sensing is the intrinsic capability to retrieve information consistently over wide areas. The developed run-off prediction method, based on machine learning and SCA MODIS time series, can thus be easily and successfully applied to different alpine basins, as shown in De Gregorio et al., 2017. Moreover, given the flexibility of this method, new relevant predictors can be easily added and tested to improve the run-off forecast. In particular, with this contribute we will give an outlook on some of new predictor variables that can be extracted from two different type of sources: 1) a new-generation of satellite data, i.e. the Sentinel missions, from which more detailed information about snow conditions, with respect to MODIS, can be extracted and 2) climate forecast data. These new possibilities will be tested within a specific case study, which is part of the H2020 SECLI-FIRM project. The project will start on February 2018 and will focus on the demonstration of how the use of improved climate forecasts, out to several months ahead, can add practical and economic value to decision-making processes and outcomes, in the energy and water sector. The proposed approach, based on machine learning and snow remote sensing products among the relevant predictors, will be tested on the SECLI-FIRM case study of the mild/dry winter 2015-16 in the Alps, where a prolonged drought caused a reduction of hydroelectric power production with an associated reduction of the volume of sold energy.

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Session 4: Operational applications in snow hydrology

Chairperson: Peter Krahe

Mysnowmaps: snow maps display and snow data crowdsourcing

Matteo DallAmico[1]; Stefano Endrizzi; Stefano Tasin[1]

[1] MobyGIS Srl, Pergine Valsugana, Italy

Email: matteo@mobygis.com

Abstract

The greatest part of annual precipitation in the Alps, above 1500 m elevation, falls in form of snow and herein remains stocked until melting time, when it returns to the hydrological cycle. When present on the mountains, snow plays a crucial role for tourism (i.e. winter sports) and is particularly observed by civil protection (i.e. avalanche hazard, roads cleaning). During the melting season, melted snow reaches hydropower dams, thus contributing to energy production,then drains downstream and recharges the water table,with benefits for agriculture. One may realize the importance of an operative snow monitoring for human activities.

Snow monitoring in the Alps is usually carried out by the avalanche warning offices: they maintain a network of stations that measure snow depth and meteorological variables at specific points. Such network is usually integrated by manual observations performed by specifically trained people. The collected data are eventually used to produce the avalanche bulletin. Although this dataset is very valuable, it cannot cover all valleys and slope and budget constraints prevent local administrations to increase the number of stations.

These considerations pose two questions: how to produce and display spatially distributed snow data in the Alps given the current dataset? How to increase the snow measure dataset?
The attempt to answer these questions has evolved in the creation of Mysnowmaps (www.mysnowmaps.com), a web/app platform dedicated to off-piste snow mountaineers. Thanks to an innovative set of software tools, it produces and displays snow information in form of maps on a daily basis all over the Alps. At the same time, it enables the users to insert their experience during the excursion, highlighting data about the snow, the track condition and the presence of critical elements (e.g. wind blown snow redistributions). The idea behind is to allow the users to plan more consciously their tours, by displaying on the same device spatially distributed snow information, meteo predictions and reviews of the excursions.

The technology behind Mysnowmaps follows a physically-based approach. Differently from the empirical statistical approach, where the snow is spatially interpolated based on a statistical regression of snow depth measures at different altitudes (Foppa et al., 2005), in Mysnowmaps snow depth is calculated by GEOtop (Endrizzi et al., 2014) solving the equations of energy and mass conservation. The input is represented by a dataset of more then 1000 meteo stations all over the Alps.
At our knowledge Mysnowmaps represents the first “Portal” displaying snow depth all over the Alps (176.000 Km2) on a continuous time and spatial scale. Other experiments on distributed maps are focused on snow covered area (e.g. Notarnicola et al., 2015) or are just related to snowfalls (e.g. meteo providers).

Furthermore, Mysnowmaps is crowd-sourcing data from outdoor users: through the App, people can share snow depth data during excursions, contributing to enlarge the snow dataset.
Finally, Mysnowmaps may be seen a tool to monitor snow water equivalent at a continental scale, improving decision making in terms of water resources estimation.

Snow Water Equivalent from operational GNSS In-Situ Stations as service for hydrological applications – ESA IAP SnowSense Demo

Florian Appel[1]; Franziska Koch[2]; Philipp Klug[1]; Patrick Henkel[3]; Monika Prasch[2]; Heike Bach[1]; Wolfram Mauser[2]

[1] VISTA Remote Sensing in Geosciences GmbH, Munich, Germany
[2] Ludwig-Maximilian-University Munich, Munich, Germany
[3] ANavS GmbH, Munich, Germany

Email: appel@vista-geo.de

Abstract

The snow water equivalent (SWE) is the key parameter of hydrological applications within the different domains of scientific, public and commercial activities. Spatially and continuous up-to-date knowledge on water stored as snow, which is released during seasonal snow melt or shorter snow melt events due to temperature increase or rain-on-snow events, has an important impact on the safety of residents and the economics. This is an issue especially for large seasonally snow-covered basins, but also for smaller scales like specific mountainous catchments. Information on the SWE, especially in context of hydrologist's daily operations (runoff and flood forecast, hydropower generation, etc.), are currently gathered from observers, automatic stations or dedicated field trips. Especially in remote areas, e.g. in Canada or Scandinavia, the density of SWE measurements is up to now still very limited and all operations (stations and field trips) are usually costly, labour-intense and/or risky.

Based on the novel GNSS snow measurement approach, which is presented by Koch et al.*, the team designed, developed and is currently demonstrating an operational service for the island of Newfoundland/Canada within the ESA IAP co-founded demonstration project SnowSense (2015-2018). The service is based on a system including autonomous GNSS based snow monitoring stations, remote sensing Earth observations (EO) of the snow cover, and the integrated hydrological model component PROMET. This combined system approach enables the provision of spatial SWE information, run-off assessment and relevant information for hydropower plant management, particularly for so far non- or sparsely equipped catchments in remote areas. The key element of the system is the novel GNSS based in-situ sensor, whereof numerous sensors are distributed at remote locations in Newfoundland. These sensors are able to retrieve the snow parameters SWE and LWC (liquid water content in snow), using the GNSS approach, and send the information via satellite communication several times a day. In combination with EO (using Sentinel-1 for wet snow monitoring) and the GNSS in situ stations, the spatially results of the PROMET model are controlled and updated to provide all hydrological parameters, which are relevant for the users and customers involved in the ESA IAP SnowSense activities.

The authors will present the latest results of the station design, the performance, the snow measurements and the hydrological products, demonstrated within the current demo operation for Newfoundland. In-situ stations are also in operation in Quebec/Canada, Germany and Switzerland. A commercial service roll-out is the overall target for the next winter.

Hydrological applications and validation of EUMETSAT-H SAF Snow products for selected river basins in Europe and Near East

Peter Krahe[1]; Simone Gabellani[2]; Peer Helmke[1]; Jaakko Ikonen[3]; Aynur Sensoy[4]; Alexander Toniazzo[5]

[1] The German Federal Institute of Hydrology, Koblenz, Germany
[2] CIMA Research Foundation, Savona, Italy
[3] Finnish Meteorological Institute, Helsinki, Finland
[4] Anadolu University, Eskişehir, Turkey
[5] Protezione Civile, Rome, Italy

Email: krahe@bafg.de

Abstract

Operational hydrological applications like monitoring of water resources and extreme events, such as floods and drought, as well as forecasting and climate change prediction services require among others spatial and temporal high resolution information about snow coverage, snow status and snow water equivalent. This information can be used for multi criteria calibration and validation of rainfall-runoff modelling or by use of data assimilation techniques for updating of initial conditions at relevant forecast times. There is a rapidly increasing number of remote sensing products with a potential application in operational hydrology. Remotely sensed images offer an opportunity to supplement ground measurements for runoff prediction during the snowmelt season. The EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF) operationally provides high quality precipitation, soil moisture and snow products derived from Earth Observation Satellites (EPS), together with their continuous quality assessment. The vision for the ongoing third phase of the initiative (CDOP-3; 2017-2022) maintains the footprints of previous phases. Besides the development, generation and consolidation of products derived from primary EUMETSAT geostationary and polar orbiting missions (MTG and EPS-SG) the use and benefits of H SAF products are promoted and evaluated in collaboration with the hydrological community. The HSAF snow products cover actually the European territory and parts of Near East. The features of the near real time available data will be presented. The usability and the concept for the validation of snow products will be discussed. Examples are given using in situ station data, snow data delineated from other satellite missions, e.g. Sentinel-2, as well modelling results for selected river basins located in Europe and Near East. Analysis and hydro-validation of H SAF snow products like snow cover and snow water equivalent gives promising results for different test sites with different topography and catchment characteristics.

Upper Chenab Snow- and Glacier Melt Runoff Modelling for Forecasting Seasonal Water Availability

Wolfgang Bogacki[1]; Markus Disse[2]; Muhammad Fraz Ismail[2]

[1] University of Applied Sciences Koblenz, Koblenz, Germany
[2] Technical University of Munich, Munich, Germany

Email: ismail@hs-koblenz.de

Abstract

Pakistan's irrigated agriculture and hence the major sector of the country's economy and GDP is heavily dependent on the water originating from the high mountain ranges of the Western Himalaya – Karakoram – Hindu Kush region. The most eastern river of which flows are assigned to Pakistan under the Indus Water Treaty is Chenab River, which enters the territory of Pakistan right upstream of Marala barrage while the whole upper catchment is located in Kashmir and Himachal Pradesh province of India. In order to decide about the actual area to be taken into command during Kharif (April – September) cropping season, a reliable forecast of seasonal flows from the upper catchments of the Indus Basin is essential. Typically, Early Kharif (April – June) flows are dominated by snowmelt while Late Kharif (July – September) flows have a significant glacier melt component and are severely influenced by occasional monsoon events, which may cause devastating peak floods.

An operational hydrological forecast model for Chenab River at Marala barrage has been developed based on an Excel implementation of the snowmelt-runoff model SRM, a temperature-index model that has proven an adequate approach for modelling runoff in large snowmelt dominated catchments with high morphologic variability and usually a sparse measuring network. In order to properly take into account the significant glacier melt flow component in Late Kharif, the original SRM approach was enhanced to SRM+G by a separate simulation of melt from exposed glacier areas.

Besides the input variable temperature, the degree-day factor is the most important model parameter. The degree-day factor for glaciers is usually considered as time-independent and only varying with geographic latitude. In contrast the degree-day factor for snow generally shows an increasing trend with the progress of the melting season and increases more rapid in higher altitudes. General degree-day factor functions for each elevation zone have been derived from a set of calibrated parameters for a series of years that were subsequently applied in the seasonal flow forecasting procedure.

For forecasting, a scenario approach has been applied that besides the actual snow-water equivalent derived from MODIS snow cover data uses, similar to the Ensemble Streamflow Prediction approach, historic meteorology as model forcings. The verification of the simulation model and the forecasting procedure with fixed model parameters and forecasting rules results in an average coefficient of determination of 0.80 and a relative volume differences of -1.1%. All year simulation runs for the period 2000 – 2014 show an average annual flow component distribution of 40-45% from snowmelt and 7-10% from glacier melt respectively. The assessment of forecast accuracy compared to observed Kharif flows shows a mean percentage bias of -1.0% and a mean absolute percentage error of 8.6% which is a substantial improvement compared to the previous statistical forecasts.

Application of remote sensing snow cover data from MODIS for seasonal flow forecast in the Syrdarya River Basin.

Olga Kalashnikova

Central-Asian Institute for Applied Geosciences, Bishkek, Kyrgyzstan

Email: o.kalashnikova@caiag.kg

Abstract

The area of the Syrdarya river basin, the second largest river in Central Asia, occupies about 782,600 km². The Syrdarya River is formed by the conjunction of two rivers, the Naryn River (basin area 59900 km2) and the Karadarya River (basin area 30100 km2). After its conjunction several tributaries conjunct with Syrdarya River delivering water from mountains around the Fergana Valley. The Syrdarya is a transboundary river with its water resources used by four Central Asian republics: Kyrgyzstan, Uzbekistan, Kazakhstan and Tajikistan. Water resources of Sirdarya river is mainly formed due to snowmelt and glacier melts and used for hydropower generation in Kyrgyzstan. Besides the use of river water for hydropower generation in the upstream countries during winter months, it is also a source for agricultural production in the downstream countries, which is not possible without irrigation due to high aridity in the summer months. The flow of rivers in the Fergana Valley and from Naryn and Karadarya Rivers varies greatly from year to year and its systematic and rational use is possible only if there is an adequate information about the current and expected water availability.

In this study, we analyzed remote sensing based snow cover data from MODIS in the Naryn, Karadarya, Shahimardan and Isfaram-Sai basins for the last 15-year period 2000-2015. Linear regression analysis were conducted to investigate dependence of river runoff during the vegetation peroid (April-September and May-September) from degree of snow covered area obtained from MODIS images processed using the MODSNOW-Tool. This information was then used to compile methods for seasonal flow prediction in the summer months for individual river basins using multiple linear regression method. Snow cover area and antecedent discharge were used as predictors to setup linear models. For some river basins with significant glacier melt contribution, the average air temperature for the month of May was also used as the third predictor to predict water availability during May-September. The temperature for this month is compiled by the Hydrometeorological Service in the first decade of April and is available for usage in forecast models.

The methods proposed for seasonal runoff forecast during summer months have a correlation coefficients (R) of 0.50-0.92, and the accuracy of the forecasts for the period from 2000 to 2015 is 77-100% when compared against observed discharge. A method of seasonal flow forecast for the Naryn basin has been implemented at the Kyrgyzhydromet since 2013 and is used by the operational units to forecast the discharge during summer months. Starting from 2018 an implementation of forecast methods proposed by the authors for the Karadarya, Shakhimardan and Isfayram-Sai rivers is planned at the Kyrgzyhydromet as well.

Session 5: Snow hydrology in semi-arid environments

Chairperson: Denis Ruelland

Streamflow simulation for high-elevation semi-arid catchments: a case study in the Vedi River of Armenia

Vazken Andréassian[1]; Hamlet Melkonyan[2]; Levon Azizyan[2]; Arthur Gevorgyan[2]; Levon Vartanyan[2]; Guillaume Thirel[3]; Simon Gascoin[4]

[1] National Research Institute of Science and Technology for Environment and Agriculture (Irstea), Antony, France
[2] HayHydromet
[3] Hydrosystems and Bioprocesses Research Unit (HBAN), Irstea, Antony, France
[4] CESBIO, University of Toulouse, Toulouse, France

Email: vazken.andreassian@irstea.fr

Abstract

We present here a detailed analysis of the hydrological behaviour of a semi-arid catchment located in the Geghama mountain range of Armenia, the Vedi River (360 km², elevation range: 1040-3060 m asl). We use daily precipitation-runoff model (Coron et al., 2017) coupled with a snow-accounting routine (Valéry et al., 2014) and benefit from a unique long-term precipitation and streamflow time series encompassing 1937 to 2015.
We first analyse the hydrologic functioning of this catchment, and study then the evolution of discharge under observed changes in climatic forcing. Last, we present simple scenarios of evolution under future climate.
Coron, L., G. Thirel, O. Delaigue, C. Perrin & V. Andréassian. 2017. The Suite of Lumped GR Hydrological Models in an R Package. Environmental Modelling and Software, 94, 166–171.
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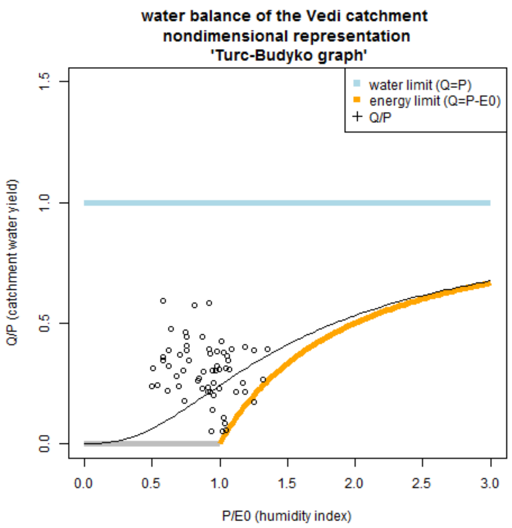

Figure 1. variability of the annual water balance of the Vedi river catchment

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Valéry, A., V. Andréassian and C. Perrin. 2014. As simple as possible but not simpler: what is useful in a temperature-based snow-accounting routine? Part 2 - Sensitivity analysis of the Cemaneige snow accounting routine on 380 catchments. Journal of Hydrology, 517: 1176-1187.

The value of remote sensing snow cover data in data-scarce semi-arid regions

Abror Gafurov[1]; Heiko Apel[2]; Sergiy Vorogushyn[2]; Andreas Güntner[2]

[1] GFZ Helmholtz-Centre Potsdam, Potsdam, Germany
[2] GFZ German Research Centre for Geosciences, Potsdam, Germany

Email: gafurov@gfz-potsdam.de

Abstract

Snow plays an important role for hydrology in many parts of the world. Especially in mountainous regions with arid and semi-arid climate, snowmelt dominates water balance. It can be stored in the mountains and released as meltwater during the warm season when demand is high for millions of people downstream. Therefore, it is important for water availability assessments to acquire snow storage in the mountains. However, observations in the remote mountains are usually rare due to limited accessibility and extreme weather conditions. Nowadays, remote sensing snow cover products deliver observations of snow state with moderate spatial and high temporal resolution, which can be well applied to acquire snow related information in meso-scale catchments.

Central Asia is one of such regions where winter precipitation falling as snow is accumulated at the high altitudes of Pamir and Tian-Shan mountains. During spring and summer months, snowmelt from these mountains dominate river flow and delivers tremendous water resources for downstream population for agricultural and energy production purposes. Thus, adequate information on snow is extremely important to assess water availability and consequently for better water resources management in the region. In this study, the value of remote sensing MODIS snow cover data for water resources assessment in several Central Asian catchments is presented. The daily snow cover time series with 500 m spatial resolution was processed using the MODSNOW-Tool for the last 17 years. In several pilot studies, the processed remote sensing snow cover data was used to estimate water storage in the region and its spatial and temporal distribution. The applications cover the operational snow cover monitoring, seasonal and monthly water availability assessment, the large-scale water resources distribution in combination with GRACE total water storage data and climate change studies. The results show the added value of remote sensing snow cover data in data-scarce regions such as Central Asia in the assessment of water resources.

Major impacts of the observed shifts in the snow regime on river flow in semiarid regions: lessons learnt from Sierra Nevada (Southern Spain)

María J. Polo[1]; María José Pérez-Palazón[1]; Javier Herrero[1]; Rafael Pimentel[2]

[1] University of Córdoba, Córdoba, Spain
[2] SMHI, Norrkoeping, Sweden

Email: mjpolo@uco.es

Abstract

Snow regime in semiarid regions shows a high variability of different time and spatial scales due to the usually large temperature intervals and the frequently torrential character of precipitation. During the last decades, significant increasing trends of the mean temperature regime had an impact on the snow occurrence and persistence; however, this has resulted in a wide range of annual and decadal hydrological impacts depending on the precipitation pattern on the daily and seasonal scales. This work focuses on the major drivers of the snow impacts on riverflow throughout the Sierra Nevada area in South Spain, facing the Mediterranean Sea, from the combination of field monitoring work at a pilot site during the last 15 years, distributed hydrological modelling and assimilation of remote data from both satellite and terrestrial imagery. The results highlight the significance of the precipitation shifts observed so far in this region rather than the temperature increase to understand the changes of the snow regime, and the need of energy balance models implemented on high resolution gridded schemes to represent the spatial distribution of the snowpack. Moreover, the general delay of the snow season and the early end of the final ablation phase result in highly variable impacts on the river flow in this area, associated to the different predominance of the underlying processes being affected by the precipitation and temperature shifts. Evaposublimation during dry and clear-sky periods, and local non-linear interactions between the snowpack and the microtopography and/or vegetation act as triggering processes of extreme events of both "snow-drought" and floods in this area. This requires a multi-scale approach to improve the snow simulation, in which the use of advanced monitoring network coupled to satellite data sources is a key resource.

The spatial and temporal distribution of snow in a semi-arid headwater, northern Mongolia

Munkhdavaa Munkhjargal[1]; Simon Groos[2]; Lucas Menzel[1]

[1] Heidelberg University, Heidelberg, Germany
[2] Dresden University of Applied Sciences, Dresden, Germany

Email: munkhjargal@uni-heidelberg.de

Abstract

The duration and spatial distribution of seasonal snow cover are crucial factors for understanding the hydrological regime in mountainous regions with semi-arid climate. For the Sugnugur valley (Khentii Mountains, northern Mongolia), a spatial analysis of mean snow cover duration (SCD) was achieved on a 30 m spatial resolution. The combination of Landsat-7, Landsat-8 and Sentinel-2 images for spatial distribution and MODIS Terra daily snow cover data (2000-2017) for temporal distribution of snow cover were used for the calculation. Validation was achieved with in situ measurements, which are time series of snow height (point data) as well as results from a snow measurement campaign. The mean increase of snow cover duration with altitude was found to be approx. 6 days/100m. However, no altitude-dependent changes in snow depth could be observed during a field campaign. For areas with similar elevation, typical snow distribution patterns occur which could be discriminated by our method: southern exposed valley slopes are either snow free or covered by intermittent snow throughout winter, due to high sublimation rates and prevailing wind. The predicted mean SCD ranges from 124 in the lower parts of the valley (around 1100 m a.s.l.) to 226 on the highest peaks (up to 2800 m a.s.l.). In comparison with a control site where snow is regularly recorded, an average underestimation of 12-13 snow cover days for 2012-2017 occurs. Shallow surface temperature measurements at different altitudes and topographic settings were also used for validation purposes and showed a good agreement (R2=0.85) with the predicted values.

Session 6: Application of remote sensing snow products in hydrological studies

Chairpersons: Abror Gafurov and Richard Kelly

Snow monitoring using Sentinel-1 and Sentinel-2 images

Carlo Marin[1]; Mattia Callegari[1]; Marc Zebisch[1]; Malcolm W. J. Davidson[2]; Claudia Notarnicola[1]

[1] EURAC Research, Bolzano, Italy
[2] European Space Agency (ESA), Paris, France

Email: carlo.marin@eurac.edu

Abstract

The availability of multi-source and multi-temporal Copernicus Sentinel images acquired over the same geographical area represents an opportunity to improve the observation of the Earth. Indeed, the simultaneous exploitation of heterogeneous data allows: i) an interpretation of the scene that is not available with data from a single observation; and ii) the improvement of the accuracy associated with data acquired from single sensors. In this work, we address the possibility to take advantage of the joint use of multi-temporal SAR and optical data to monitor the snow cover. From these two data sources, we propose a robust approach that is able to: i) deal with the missing information about the presence/absence of snow due to the cloud coverage; ii) improve the classification of wet snow; and iii) extract the information related to the status of the snow i.e., dry or wet snow. The proposed multi-temporal approach uses a fusion schema based on a set of consensus rules applied at the decision level that takes into account both the snow variability with respect to the difference in the sampling time of the multi-source data and the propagation of the error. The proposed approach is validated considering the real example of snow monitoring using Sentinel-1 and Sentinel-2 data over the Sarntal catchment in South Tyrol, Italy. The results confirm that the proposed approach allows the improvement of the snow monitoring performance associated with the use of the single sensors.

Influence of black carbon on physical properties of snow using remote sensing and field based spectroradiometer data. A case study from Dhundi to Solang, Western Himalaya

L. N. Sharma[1*], Snehmai[2], Chander Shekhar[2], Pramod Kumar[1], Navin Kumar[1]

[1] Department of Applied Sciences, PEC (Deemed to be University), Sector-12, Chandigarh, India
[2] Snow & Avalanche Studies Establishment, Him Parisar, Secto-37A, Chandigarh, India

Email: lnsharma.pec@gmail.com

Abstract

Snow undergoes constant change becomes essential matter in earth's climate and hydrological system. In India snow covered areas are found in rugged terrain of Himalayas. Remote sensing data provide timely and efficient information for spatio-temporal changes with reference to snow studies for inaccessible terrain. A study was undertaken to understand influence of black carbon on physical parameters of snow i.e grain size, density, wetness, temperature, reflectance based on ground truth data collection and satellite data of hyperion and Landsat. The reflectance was measured using spectroradiometer from the Dhundi –Solang area during Jan-February 2017. The AOI was clipped from SOI toposheet at 1:50000 scale. Black carbon samples were collected from the snow surface and analysed using Carbon Analyzer. For physical parameter estimation, multispectral and hyperspectral satellite data were digitally processed using ERDAS Imagine, ArcGIS and ENVI softwares. Landsat-8 data of October 2016 and Hyperion data of January 2016 were used for generating surface temperature map and snow grain size studies. Out of 220 bands of hyperion, selected bands only used for processing. Pre-processing involved removal of bad bands, bad column and removing the influence of the atmosphere. FLAASH atmospheric correction model is applied on Hyperion data to retrieve surface reflectance in ENVI 5.1 software. Snow grain size has been estimated using spectral angle mapper (SAM). Spectral reflectance curves of fresh snow were generated in field, using spectroradiometer and compared with results derived from hyperion derived spectra was found to correlate well with observed data. Snow has high reflectance in visible and low in SWIR. Sam classification has brought out percentage of fine, medium and coarse grain size of snow. It is established that black carbon reduces reflectance in visible region substantially as revealed from Snow, Ice, and Aerosol Radiative model. Thus, it is concluded that by integrating results of image processing of remotely sensed data with field based measurements including spectroradiometer brought out influence of black carbon on snow physical properties and provided more accurate estimation of snow parameters.

Investigation and modelling of penetration depth of TanDEM-X Interferometric SAR Data over the Greenland ice sheet

Sahra Abdullahi; Birgit Wessel; Martin Huber; Tobias Leichtle; Achim Roth

German Aerospace Center (DLR), Wessling, Germany

Email: Sahra.Abdullahi@dlr.de

Abstract

Polar regions pass through dramatic changes caused by ongoing climate warming. In many areas, rapid retreat of glaciers and ice sheets has been observed within the past decades, which leads to significant consequences globally. In order to understand and predict these complex processes and their impacts on the environment as well as on human systems, detailed and area-wide information on the environment's response to climatic changes is required. Interferometric SAR systems enable the derivation of 3-d information independent of cloud cover and illumination, and thus offer an efficient technique to collect information on glaciers and ice sheets worldwide, especially with respect to polar regions in high latitudes. However, these interferometric elevation data suffer from penetration of the SAR signal into the snow and ice surface. In this context, the aim of this study is to investigate the penetration depth of interferometric X-band SAR data in order to provide reliable and accurate elevation measurements. The TanDEM-X mission is well suited for monitoring of the Earth's snow and ice cover due to the global availability of consistent and precise interferometric data. In particular, we use interferometric bistatic StripMap TanDEM-X acquisitions and IceBridge ATM L2 Elevation data from spring 2012 in order to analyze the penetration depth of the signal. Different snow and ice characteristics determine penetration-dependent backscatter behavior. Relevant physical parameters that influence the SAR backscatter and accordingly the penetration depth of the signal include grain size, snow density, stratigraphy, surface roughness, and water content. According to these characteristics, snow zones corresponding to different snow morphologies can be distinguished. Against this background, we explore penetration depth of interferometric TanDEM-X elevation data with respect to different snow zones over the Greenland ice sheet. We observe penetration depths up to ten meters and a high correlation between penetration depth and backscatter intensity as well as interferometric coherence. For the purpose of improving the vertical accuracy of global TanDEM-X elevation data, we model penetration depth based on backscatter intensity and interferometric coherence and will present first results for a test site on the Greenland ice sheet.

Fusion of remote sensing and hydrological model data for improving snow mapping

Ludovica De Gregorio[1]; Mattia Callegari[1]; Carlo Marin[1]; Marc Zebisch[1]; Lorenzo Bruzzone[2]; Begum Demir[2]; Ulrich Strasser[3]; Daniel Günther[3]; Claudia Notarnicola[1]

[1] EURAC Research, Bolzano, Italy
[2] Universty of Trento, Calepina, Italy
[3] University of Innsbruck, Innsbruck, Austria

Email: Ludovica.DeGregorio@eurac.edu

Abstract

Snow is a water resource that plays an important role in hydrological cycle in mountainous areas. Traditional methods for snow mapping are based on meteorological stations acquisitions which, however, cannot provide information in remote areas.

In this context, remote sensing can make a significant contribution, by increasing spatial resolution with respect to conventional methods. Nevertheless, also this method shows some limitations related to the use of visible bands (clouds, forest cover, shadow…).

Employing numerical models is another common approach for gaining information about snowpack. Starting from energy and mass balance of snowpack, physically-based models can predict many snow properties (snow depth, albedo, temperature…). However, even though extensively tested and validated in well-equipped areas, these models are still subject to rather large uncertainties in spatially distributed applications. These uncertainties are due to the fact that such models rely on meteorological forcing, which need to be regionalized from point observations and therefore are prone to errors, especially in mountainous environments.

Consequently, the jointly use of remote sensing and physically-based models has received an increased attention in the last years. The detailed spatial representation, typical of remote sensing, makes it suitable for the extension in ungauged sites, where models fail to provide a parameters estimation due to the lack of input data. Most common approaches are the use of remotely sensed products for model calibration or data assimilation. The dynamical incorporation of remotely sensed data into the model involve a massive amount of operations by making these approaches complicated.

The aim of this work is the introduction of a new concept of decision fusion by exploiting physical model simulations and remotely sensed products and their uncertainties. The innovative aspect of this approach is that the fusion, made by means of Support Vector Machine (SVM) technique, involves the final products of remote sensing and model, differing from described approaches where remote sensing is mainly used for model tuning.

The work involves a hydroloclimatological model (AMUNDSEN [1]) products and MODIS snow cover maps [2], both at 250 m ground resolution. Higher resolution images (Sentinel 2 and Landsat 8 products) have been used as reference dataset. Exploiting information deriving from uncertainties of two approaches, fusion aims to improve the estimation in areas where they disagree.

Collected samples have been randomly divided, by using 30% of data as test dataset and 70% as training dataset. First results show a Pearson correlation coefficient R equal to 0.86 and an accuracy of 0.95.

Most of errors from MODIS classification derive in detecting snow free areas: 65% of test points have been wrongly classified as snow covered. This percentage decreases to 12.2% in model classification and reaches 2.4% in fused product.

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Monitoring snow cover extent with satellite synthetic aperture radar for snow hydrological applications

Arnab Muhuri[1]; Avik Bhattacharya[1]; Lucas Menzel[2]

[1] Indian Institute of Technology Bombay, Mumbai, India
[2] Heidelberg University, Heidelberg, Germany

Email: bikearoundmumbai@gmail.com

Abstract

Recent studies have highlighted the depleting trend of snowfields and receding glaciers in parts of the Hindu-Kush Himalayan (HKH) region. It is believed that the onset of this recession commenced during the mid-19th century (Bolch et al., 2012). A number of glaciers situated outside the Karakoram region have demonstrated ablation patterns. Since the HKH region is the source to some of the major Asian river systems, such exhausting trends of glacier volume has risen concerns for the water resources. Therefore, in order to resolve such uncertainties a reliable snow cover monitoring technique capable of monitoring snow cover is much desired.

In the recent past the Touzi scattering asymmetry parameter has been utilized for segregating tree species over a wetland based on the diversity of their leaf structures (Touzi et al., 2009). The scattering asymmetry defines the corresponding randomness in scattering mechanism denoted by each Eigen component. We propose a seasonal approach to monitor snow cover over the Indian Himalayas by exploiting the variation in the scattering asymmetry that occurs by virtue of the metamorphosing matrix of the snow crystals (Muhuri et al., 2017).

Such an information is useful for various applications over snow covered areas, snow hydrological modelling being one of them. Satellite remote sensing is a crucial tool for large scale monitoring applications due to its high spatial coverage, temporal repetivity, and diverse imaging configurations available among the state-of-the-art airborne \& spaceborne imaging sensor platforms. Such characteristics can play a vital role in remotely retrieving snow parameters for hydrological modelling and applications. Traditional modelling and snowmelt runoff forecasting practices involve field sampling of the principal model parameters, which is labour intensive and hence, both time consuming \& expensive, and prone to systematic sampling errors. With the advent of remote sensing platforms spatially detailed snow parameter maps can be acquired in cost effective and timely manner. Moreover, high-resolution satellite systems have rendered spatial decrease of the sampling intervals, which in turn has resulted in refinement of the model outcomes. Such an accurate and meticulous forecasting approach is essential for operational hydrological applications like water discharge potential for a hydrological response unit (HRU).

Thus far, the Snowmelt Runoff Model (SRM) is the only reliable runoff forecasting model which computes snow covered area with remotely sensed snow cover data as one of its input variables. Hydrological models in practice are predominantly optimized for data sources other than remotely sourced information from airborne/spaceborne platforms. As a consequence of this, due to limited options available remotely sensed Earth observation datasets are under-utilized in hydrological applications despite the synoptic capabilities of sensor platforms to survey the drainage basin.

In this paper, we present a perspective to integrate remotely sensed snow cover information extracted from satellite images along with meteorological data logged by field weather stations in the SRM for snow hydrological modelling.

Ku and X-band observations of seasonal snow in tundra, alpine and maritime snow landscapes

Richard Kelly; Aaron Thompson

University of Waterloo, Waterloo, Canada

Email: rejkelly@uwaterloo.ca

Abstract

Recent remote sensing field experiments using active microwave observations of seasonal snow have focused on understanding the Ku- and X-band frequency backscatter responses from snow, and have provided the impetus for developing satellite-based instrument technologies with global applicability, such as ESA's CoReH2O. This paper brings together science knowledge from five recent field experiments conducted in North America to characterize the sensitivities of Ku and X-band microwave signatures to snow water equivalent (SWE). Ku and X-band scatterometer experiments have been conducted in the Northwest Territories, Manitoba, Ontario and the Colorado Rocky Mountains to characterize the backscatter sensitivity to SWE. The experiments show that while backscatter signals at Ku are indeed sensitive to SWE, snowpack structural properties (especially grain size, density and discrete layering) are also factors influencing the radar response. Notwithstanding these factors, this paper also explores the outstanding question regarding how radar observations at these frequencies from satellite or airborne instruments can be leveraged to produce scale-relevant estimates of SWE.

On the unknown precipitation amounts of high-elevation catchments: can we use MODIS images to infer precipitation-elevation gradients?

Vazken Andréassian[1]; Guillaume Thirel[1]; Philippe Riboust[1,2]; Simon Gascoin[3]

[1] National Research Institute of Science and Technology for Environment and Agriculture (Irstea), Antony, France
[2] University of Sorbonne, Paris, France
[3] CESBIO, University of Toulouse, Toulouse, France

Email: vazken.andreassian@irstea.fr

Abstract

High-altitude catchments are a real challenge to the hydrologist: (i) because precipitation gaging networks are often sparse, (ii) because most of the maintained precipitation gages are often located at the lower elevations, and (iii) because of the metrological difficulties associated with measuring snow fall. The common approach consists in extrapolating precipitation amounts from all available precipitation gages using so-called precipitation-elevation gradients (Barry, 1992; Valéry et al. 2010). MODIS images offer a possibility to map solid precipitations which accumulate during the winter season. And although satellite images offer (almost) no clue concerning the snow water equivalent, the time taken by snowpack to melt can offer a guess of total snowfall. We test this hypothesis on two high-elevation catchments in Armenia (Table 1 and Figure 1).

Table 1. Characteristics of the catchments studied here

		Elevation [m]		
	Area [km²]	min	median	max
Kasakh River	440	1850	2170	3980
Vedi River	360	1040	2050	3060

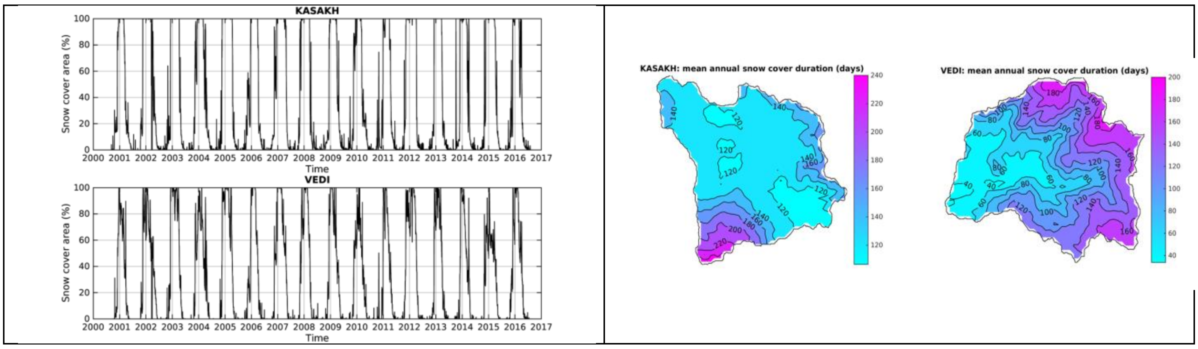

Figure 2. MODIS-derived mean annual snow cover on the Kasakh and Vedi Rivers

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Valéry, A., Andréassian, V. and Perrin, C. 2010. Regionalization of precipitation and air temperature over high-altitude catchments – learning from outliers. Hydrological Sciences Journal, 55(6): 928-940. DOI: 10.1080/02626667.2010.504676

A portfolio of snow products based on Sentinel-3 for snow hydrology

Rune Solberg[1]; Øivind Due Trier; Øystein Rudjord; Jarle Hamar Reksten

[1] Norwegian Computing Center, Oslo, Norway

Email: rune.solberg@nr.no

Abstract

Seasonal snow is an important component of the Earth system heavily affecting the energy balance and the water cycle at high latitudes and elevations. Vast land areas in the north and in mountainous regions are weakly monitored by in situ sensors due to the fact that most of these regions are sparsely populated. Earth observation is the only practical means of frequent and accurate monitoring of snow properties in these regions.

This presentation gives an overview snow algorithms and products that have developed for MODIS over more than 15 years and are now being ported, adapted and optimised for the use of Sentinel-3 data. The Sentinel-3 sensors Ocean and Land Colour Instrument (OLCI) and Sea and Land Surface Temperature Radiometer (SLSTR) together represent a powerful set of instruments for monitoring of properties of the seasonal snow cover. The revisit time is 0.5-1.0 day over most regions with seasonal snow cover (with two satellites).

Optical snow products developed in the MODIS era include snow cover, snow surface temperature, snow grain size, snow surface wetness, snow surface hoar, snow spectral albedo, snow impurities and black carbon in snow. Several of these variables are important in snow hydrology. Snow cover is a key to warning of potential flood situations, and snow surface temperature and snow surface wetness gives information on the progress towards and within the snowmelt season. Snow surface albedo is crucial in energy balance modelling and modelling the snowmelt progress. State-of-the-art distributed hydrological models model these and more variables that may be validated and/or updated from satellite observations.

In advanced operational snow hydrology satellite observations and models are used together. Due to this we are now developing a similar portfolio of snow products based on Sentinel-3 data to be applied by The Norwegian Water Resources and Energy Directorate (NVE). This presentation will go through the algorithms for the different products and compare retrieval results from MODIS and Sentinel-3. As there is no one-to-one match in general between the bands of MODIS and SLTSR/OLCI, we had to make algorithmic changes and adaptations. The related challenges will be discussed, and the performance between the two compared.

Producing cloud-free MODIS snow cover products for SW Germany through the application of conditional probability interpolation and meteorological data

Chunyu Dong[1]; Lucas Menzel[2]

[1] University of California, Los Angeles, United States
[2] Heidelberg University, Heidelberg, Germany

Email: chunyudong@ucla.edu

Abstract

Cloud cover and snow misclassifications are the two major limitations for the hydrological application of MODIS snow data. Ground-based meteorological data have the inherent potential to provide the means to reconstruct snow cover for regions in which MODIS snow maps are obstructed by clouds, and to reduce misclassified snow observations. In this study, a multistep method is developed to generate cloud-free MODIS daily snow cover products. The accuracy of the updated MODIS snow products is evaluated for a region in southwestern Germany in which winter cloud coverage and snow variability are typically high. First, we applied Aqua/Terra combination, temporal combination and spatial combination to reduce the cloud coverage and to retrieve the omitted snow. This procedure was not effective since cloud blockage occurs frequently during the snow season. A conditional probability interpolation was then employed to reclassify the remaining cloud cover on MODIS snow maps based on in situ snow depth observations. Finally, we implemented a set of meteorological filters to minimize the misclassified snow in MODIS snow products. The improved cloud-free MODIS daily snow maps showed an overall accuracy of about 92% during the snow season with significantly reduced snow overestimation errors and a slight increase in snow omission errors, compared to the overall accuracy of 87% and 94% for original MODIS Aqua and Terra data, respectively. This study suggests that the fusion of ground-based and satellite based snow observations is an effective approach for generating cloud-free remote sensing snow data.

Session 7: Open session on snow hydrology

Chairperson: Lucas Menzel

Evolution of snow cover stratigraphy during ablation period in High Arctic tundra environment (SW Spitsbergen)

Daniel Kepski[1]; Bartlomiej Luks[1]; Krzysztof Migala[2]; Aleksander Uszczyk[3]; Sebastian Westermann[4]; Tomasz Budzik[3]

[1] Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland;
[2] University of Wrocław, Warsaw, Poland;
[3] University of Silesia in Katowice, Katowice, Poland;
[4] University of Oslo, Oslo, Norway

Email: d.kepski@igf.edu.pl

Abstract

In the High Arctic snow cover persist on the tundra during majority of the year, influencing growth of plants, ground thermal regime and determining food availability for herbivores. Besides snow cover onset and duration, snow pack stratigraphy plays important environmental role, reflecting weather conditions since the beginning of accumulation season. For example, rain-on-snow events during the winter may initiate creation of basal ice or ice layers within the snowpack. Such layers may hinder herding of reindeers and affect percolation of water and heat fluxes inside the snowpack. The most dynamic snow metamorphism processes occur in spring, when positive air temperature begin to prevail. Snow melting process not only change previous stratigraphy, but also depends on it, as ice layers may protect bottom snow layers from the influence of percolating water.

We present evolution of snow cover physical properties in four locations representing different types of unglaciated coastal area of southern Spitsbergen: wind exposed flat plain, foot slope, frozen lake and accumulation place on an edge of a river valley. Data were collected in Spring 2016, when regular measurements were performed in snow pits in in weekly manner. First snow pits were dug on 11th of April, before the start of snowpack ablation. Measurements lasted till the end of May, when only snow patches remained on the ground. Observations from snow pits were compared with snow stratigraphy profiles computed with SNOWPACK model (Bartelt and Lehning, 2002). Different model setups were tested, where first observations from the field were used as an initial snow conditions for the numerical model calculations. Model predictions were validated after every week with data from in-situ measurements. Special attention was given to differences between observed and simulated snow water equivalent in particular ablation stages.

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Factors to consider for improving rain snow parameterization in surface based models

James Feiccabrino

Lund University, APO-AE, Germany

Email: james.feiccabrino@googlemail.com

Abstract

Accurate precipitation phase determination is a primary necessity for surface based hydrological, ecological, safety, and climate models in cold regions. Unfortunately, precipitation phase at earth's surface is a result of cloud and atmospheric properties which often occur at a sub-daily timescale, and are not measured by surface weather stations. Many hydrological and engineering models use surface temperature data at a daily timestep. However, there is a plethora of weather stations reporting sub-daily surface weather observation, and many of these stations report parameters that could be used in place or in conjunction with air temperature to improve precipitation phase parameterization. The use of hourly or 3-hourly data gives both conditions occurring during sub-daily precipitation events, and allows the ability to infer atmospheric conditions above the surface weather station based on meteorological cyclone theories and other similar studies.

This study uses 681,620 weather observations with an air temperature (AT) -3 to 5C and an identified precipitation phase occurring during the observation to identify thresholds for different precipitation phase determination schemes (PPDS). This dataset represents 38 and 42% of precipitation observations over a 16 year period for 85 and 84 Swedish and Norwegian weather stations respectively. A second data set consisting of three years of observations for the Norwegian sites was used to verify the results. The misclassified precipitation (error) from PPDS using AT, dew-point temperature (DT) and wet-bulb temperature (WB) thresholds were compared using a single threshold PPDS. The Norwegian observations between -3 and 5C resulted in 11.64, 11.21 and 8.42% error for DT (-0.2C), AT (1.2C) and WB (0.3C) thresholds respectively. Individual station thresholds had a range of -0.7 to 1.2C, -1.2 to 0.9C, and -0.1 to 2.5C for WB, DP, and AT respectively.

Optimal PPDS values and methods should differ between landscapes due to contrasts in land atmosphere energy exchanges. Therefore, the 169 stations were then categorized into landscapes of; windward (WW) ocean, WW coast, WW fjord, WW hill, WW mountain, leeward (LW) mountain, LW hill, LW rolling hills, and LW coast. This landscape classification was based on location relative to the Scandinavian Mountains, and the % water or terrain roughness value within 15KM.

These results were then ran again using the 3, 6, 12, and 24 hour temperature values to compare the relative influence of time scale on PPDS errors.

PPDS methods requiring sub-daily time steps, or observed elements at the time of observation were also tested. These observation groups include; 1.) occurring before and after an air mass boundary, 2.) with different water temperatures and/or NAO phases, 3.) with snow cover, and 4.) with different cloud heights. In Norway, it was found that as the unsaturated layer depth beneath clouds increased from 0 – 1000m, AT thresholds warmed. Cloud height adjusted AT thresholds reduced error by 5% before threshold adjustments for landscapes.

Snow avalanche activity recorded by tree-rings in Rodna Mountains (Eastern Carpathians), Romania

Lonela Gavrila; Olimpiu Traian Pop; Flaviu Mesesan; Cosmin Timofte; Csaba Horvath

Babes-Bolyai University, Cluj-Napoca, Romania

Email: gvrl_oana@yahoo.com

Abstract

Snow avalanches are widespread process in high massifs belonging to Romanian Carpathians range. The sudden and unpredictable occurrence of snow avalanches cause damage to forest vegetation, infrastructures, transportation roads and sometimes loss of life. Understanding the process activity is therefore crucial for hazard prediction and mitigation measures. Trees register in their yearly increment rings the effects of mechanical disturbance caused by external processes being natural archives of hydrological and geomorphic activity on timescales of decades to centuries. On the forested slopes affected by snow avalanches, where historic records are lacking, tree-ring analysis is a good alternative to reveal an accurate chronology of events. In this context, the aim of our study is the reconstruction of snow avalanche activity (spatial distribution, runout distance, frequency) with one-year resolution using data recorded in trees growth-rings on the southern slope of Piatra Albă Peak (2034 m a.s.l), in Rodna Mountains (Eastern Carpathians). To perform this research a total of 60 Norway spruce trees (Picea abies (L.) Karst.) and Abies alba) showing indication of past snow avalanche activity (scars, tilted trunks, broken crown or branches) were sampled along the path. Analyses of growth reactions (e.g. scars, traumatic resin ducts, compression wood, growth suppression) from the sample collection (cores and discs) provided the chronology of snow avalanche events back to the mid 20th century. A minimum frequency of snow avalanches was calculated based on the number of trees showing growth disturbances for each of the reconstructed years. High-magnitude avalanche years and corresponding growth disturbances were mapped to visualize the minimum extent of each event. Data obtained will help improving of limited archival records and allowing a more realistic estimation of process occurrence in the study area. The knowledge that tree-ring analysis furnished to magnitude-frequency relationships and the spatial patterns of past snow avalanche, will support future hazard mitigation in the area.

Teaching snow hydrology - A research related educational concept for undergraduate programs

Roswitha Stolz[1]; Tobias Hank[2]

Ludwig-Maximilian-University of Munich, Munich, Germany

Email: r.stolz@lmu.de

Abstract

Snow hydrology, because of its distinct small and regional scale effects on the water balance, provides perfect examples to guide undergraduate students towards systematic quantification of land surface characteristics. Different methods to determine snow hydrological parameters, ranging from destructive point measurements to large-scale area-based remote sensing techniques, are currently applied in state-of-the-art snow science. Investigating different snow quantification methods thus is particularly suitable to give undergraduate students insights into the processes of scientific work.

The undergraduate program of Geography at the LMU Munich schedules a project seminar, compulsory for third year bachelor students, which is supposed to pave the way for the career entry of the soon to be Bachelors. During the last three years, the authors developed, evaluated and refined a teaching concept, which is based on simulating a third-party-funded research project with the aim to determine the seasonal development of snow parameters in a small catchment in the Bavarian Alps. While the lecturers play the role of funding agencies, the participating students act as applicants and submit research proposals. The elaboration of the proposal is framed by lectures on project management, snow expert talks and hands-on training with snow measuring gear. In the course of the project, the students create spatially explicit maps of snow hydrological parameters such as water equivalent, snow height, snow cover extent etc. The different steps include the handling of meteorological data, the processing of satellite data (optical and radar) as input into a simple snow hydrological model, the application of different model steps to calculate temporal development of SWE and finally the planning and implementation of a field campaign to validate their model results. The final presentation of results is organized as a public poster presentation.

Disguised as a management game, all objectives of the seminar are fulfilled. On one hand, students become familiar with procedures of organizing, administering and conducting research projects from announcement of opportunity to final presentation. At the same time, the participants pick up state-of-the-art developments in snow hydrology and cryo-science. The authors believe that the concept of the seminar includes aspects of high practical relevance for potential careers of the future graduates and thus recommend its implementation.

Teaching snow-related concepts in the Romanian university curricula. Study case – Faculty of Geography, University of Bucharest

Laura Comanescu; Alexandru Nedelea

University of Bucharest, Bucharest, Romania

Email: lauracomanescu@yahoo.com

Abstract

Teaching about concepts, theories and investigation methods on snow related processes are included in the university curricula predominantly at the Faculty of Geography (9 faculties or departments in Romania) with various degree of weight depending on the specificity of each university centre. The analysis of curricula, courses structure and discussions with the teaching staff and questionnaires done with students show that the Faculty of Geography within the University of Bucharest provides the largest number of hours to the study of snow processes both within its undergraduate and master programs.

Thus, the graduate program has four courses (General Hydrology, Meteorology, Climatology, General Geomorphology) whose contents specifically states that will create competences related to: hydrology research methods (including snow), precipitations (including solid processes): genesis, classifications, geographical distribution of snow falls and snow layer, the role snow has as a geomorphological agent (periglacial relief) or the manner in which snow forms (glacial relief). Within its 6 master programs elements related to snow and its dynamic are studied more deeply and from different perspectives (atmosphere circulation and solid precipitation formation, the impact of these precipitations on aircraft travel, remote sensing of snow properties, GIS modelling and thickness of snow layer, slope dynamic in a periglacial regime through avalanches, avalanche forming conditions and typology, organizing the Carpathian mountainous areas with the risk of avalanche forming, the ratio between geographic risks and tourism activities).

Our discourse's aim is to establish the vision of the teaching staff and students on how they perceive the way in which information on snow processes is taught in the classroom and in the field; the methods, techniques, and means used to this end and their efficiency as well as the competences achieved. Special attention will be given to the role that practical and applicative field activities have in attaining snow-related knowledge.

Zoning the territory of Kazakhstan for snow loads

Aliya Nurbatsina

RSE Kazhydromet, Almaty, Kazakhstan

Email: aliya.nurbatsina@gmail.com

Abstract

The purpose of this work is mapping snow loads (water reserves) and determine the patterns of their distribution across the territory of Kazakhstan. Kazakhstan is included to the zone of seasonal snow cover and only its high-mountainous areas can be referred to the zone of eternal snows. Water content of snow cover is unevenly distributed throughout the Kazakhstan. The water reserve of snow (maximal of the largest) is 139 mm in average for the northern Kazakhstan, 119 mm - for the central Kazakhstan, 126 mm - for the western Kazakhstan, 230 mm - for the eastern Kazakhstan, 106 mm -for the southeast and southern Kazakhstan. The areas of eastern and northern Kazakhstan have elevated values of water content of snow. There are increase in water reserves of snow with altitude in the mountainous areas.

For calculating snow loads, the Gumbel method recommended by Eurocode was used. Calculations were made according the empirical data observations of the maximal water reserve of snow on the field routes over the studied period of 40 years. Methods of zoning snow characteristics were developed during the work, including: empirical-statistical methods, cluster and regression analyzes, recommendations and working instructions for constructing meso-climatic maps in the GIS-technology system. As a result of the work, the following climatic maps are constructed: 1) Zoning of the territory of the Republic of Kazakhstan for snow loads to the ground (the characteristic value, determined with an annual probability of exceeding 0.02 or 1 time in 50 years); 2) Zoning of the territory of the Republic of Kazakhstan for extreme snow loads to the ground (as a result of snowfall with exceptionally low probability); 3) Zoning of the territory of the Republic of Kazakhstan for snow loads to coverings, caused by extreme snowbound, according to Annex B, Eurocode 1991-1-3 (as a result of the stratification of snow with extremely low probability); 4) Zoning of the territory of the Republic of Kazakhstan (including mountainous areas) by climatic zones linking the altitude of the terrain and snow load.

A first gridded rain-on-snow product derived from passive microwave remote sensing for Alaska

Caleb Pan[1]; Peter Kirchner[2]; John Kimball[1]; Jinyang Du[1]; Youngwook Kim[1]

[1] University of Montana, Missoula, United States
[2] National Park Service, Alaska, United States

Email: caleb.pan@mso.umt.edu

Abstract

Rain affect all of the physical properties of snow including energy content, depth, density, water content and grain size. In northern latitudes rain-on-snow (ROS) and the proceeding icing events effect ecosystem processes at multiple spatial and temporal scales including hydrology, carbon cycling, wildlife movement and human transportation. In this paper, we present the first gridded ROS product derived from 6-km2 AMSRE/2 Tb data for water years 2003- 2016 across the state of Alaska. The two-tiered validation approach presented high accuracies across multiple spatial and temporal scales. Specifically, tier-1 produced accuracies ranging from 75-100 % drawing from empirical observations, and station observations and measurements in Fairbanks, AK. From 53 climate stations distributed across Alaska, tier-2 produced an acceptable overall accuracy of 85.9 %. We found that ROS events possessed both spatial and temporal variability throughout the study period. Annual variations in ROS events corroborated well with temperature anomalies and occurred most frequently in November and December. ROS events were consistently observed in the Bering Sea Coast and Alaska Gulf Coast regions, while they occurred in periods of above normal temperatures in the Interior and North Slope regions. Future research will be directed towards incorporating landscape heterogeneity (forest cover, small lakes, and elevation gradients) to improve the overall identification of ROS events.

The triggering of remote controlled avalanches in the Romanian Carpathians. Capra Valley case study (February 2013)

Alexandru Nedelea; Anca Munteanu; Laura Comanescu

University of Bucharest, Bucharest, Romania

Email: alexnedelea10@yahoo.com

Abstract

The artificial release of avalanches represents a necessity for the mountain areas with important socio-economic activities also during the winter season. Taking into acount their practical implications, various more and more perfected systems (some of them with remote control) for artificial release of avalanches have been developed in the mountain areas from Europe and North America. For the artificial release of avalanches in the Romanian Carpathians on 26 February 2013 the system Daisy-Bell was for the first time used. For this experiment the Capra challet neighbouring area was chosen (Southern Carpathians, southern slope of Făgăraş Mountains, along Transfăgărăşan road) because of the fact that it concentrates both transport infrastructure (the high altitude road of Transfăgărăşan) and tourism infrastructure (cable transport, challets, hiking paths accessible also during winter). Moreover this area is placed on the mountain range which registers the highest number of avalanches and respectivelly the highest number of avalanche victims (tourists, skiers, alpinists) in the Romanian Carpathians. The investigation methodology comprised several phases: the synthesis of the existing information in the scientific literature about the Daisy Bell system, about Capra valley area and about the avalanches in the entire Carpathian mountains; data gathering on the field during the experiment on Capra valley (information gathered from the members of Salvamont teams, about the existing conditions, the timing of the flight, the encountered difficulties, the pathway, the detonation points and effects); the mapping of avalanche susceptibility for slopes within the study area (indicating the detonation points and the existing infrastructure); the analysis of the meteorologic conditions at the moment of the experiment (data mining performed on the meteorologic stations within the area or in the neighbouring regions as well as on specialized sites). The action was prepared a long time ahead so that the meteorologic conditions and respectively the field research results could not have been estimated. Although the detonation in three different points was attempted an avalanche could not be produced, also because of the reduced visibility (nebulosity and fog) which prevented the helicopter from reaching the level of the crest or areas where snow had not flown yet.

The paper aims to analize the meteorological conditions and the snow layer existing at that moment. Before the event, snow falls which determined the accumulation of a snow layer of approximately 15 cm were registered, as well as strong winds with a speed over 70km/h which determined blizzards and snow deposits in sheltered spaces which further on generated windmills (especially on the north oriented slopes). Although there was enough snow many avalanches had been produced several days before as weather got warmer. The water resulted from snow melt penetrated the snow layer and moistened it so that it became heavier and acted as an extraweight on the layer located above the crusts. The snow structure showed the existence of round grains within the snow layer (on the south oriented slopes) while on the nothern slopes the cup crystals domined.