# Workshop Report 1st Snow Data Assimilation Workshop in the framework of COST HarmoSnow ESSEM 1404

## Short title:

Workshop Report 1st Snow Data Assimilation Workshop


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## Abstract

The 1st Snow Data Assimilation Workshop in the framework of COST HarmoSnow ESSEM 1404 took place in Offenbach, Germany, on 8-9 March 2017. Of particular relevance for the workshop were thematic sessions on i) data assimilation methods and the use of snow observations, ii) snow observations and evaluation, iii) snow observations and physical snow models, and iv) snow observations and hydrological models. This report summarises the scientific contributions presented and the open scientific questions discussed at the workshop. The main focus of the discussions was on methods for combining satellite observations with conventional in-situ snow measurements and modeling results and on spatial and temporal representativeness errors of snow measurements for data assimilation in NWP and hydrological models.

# Introduction

Proper description and assimilation of snow information into hydrological, land surface, meteorological and climate models are critical to address the impact of snow on various phenomena, to predict local snow water resources and to warn about snow-related natural hazards. This induces a challenging problem of bridging information from micro-structural scales of the snowpack up to the grid resolution in models. International research teams have developed different snow measurement practices, instrumentation, algorithms and data assimilation techniques customised to their purposes. However, they lack harmonised approaches, validation and methodologies. The HarmoSnow COST Action co-ordinates efforts to address these issues, through establishing harmonized monitoring practices, enhancing the use of observations by promoting new observing strategies, bringing together different communities, facilitating data transfer, upgrading and enlarging knowledge through networking, exchange and training, and linking them to activities in international agencies and global networks.

In the framework of the COST Action HarmoSnow ESSEM 1404 the first Snow Data Assimilation Workshop took place at Deutscher Wetterdienst, Offenbach, Germany from 8 to 9 March 2017. The main aim of the workshop, attended by 19 participants from 12 countries including 10 operational weather services, was to address the following topics

- Data assimilation methods and use of snow observations
- Snow observations and evaluation
- Snow observations and physical snow models
- Snow observations and hydrological models.

The workshop also included discussions of methods for combining satellite observations with conventional in-situ snow measurements and modeling results and on spatial and temporal representativeness errors of snow measurements for data assimilation in NWP and hydrological models.

The detailed agenda and PDFs of most of the presentations are online available from the COST HarmoSnow website: http://www.harmosnow.eu/

# Data assimilation methods and use of snow observations

Snow observations are required for hydrological and meteorological forecast models through the water cycle and thermodynamic exchanges. They are also used for calibrating, validating and updating these models. Numerical weather prediction (NWP) models relate prognostic snow description to observations via integrated data assimilation (DA) procedures. Operational models performance would benefit from regular transmission of real-time space-borne snow data, which are also necessary for research and developing the models. The contribution of Dong et al. showed the importance of using remote-sensing satellite products, e.g., the Interactive Multi-Sensor Snow and Ice Mapping System (IMS) to force land-surface models with NASA LIS (integrated modeling and DA framework). The current NASA LIS (version 7) integrates NOAA operational land surface and hydrological models (NCEP's Noah, versions from 2.7.1 to 3.3 and the future Noah-MP), high-resolution satellite and observational data, and land DA tools. The existing land DA capabilities in LIS have been transitioned to support NCEP's land surface assimilation of satellite-based soil moisture and snow observations. A set of offline numerical experiments driven by the GFS forecast forcing have been conducted to evaluate the impact of assimilating snow with daily Global Historical Climatology Network (GHCN). The statistics from LIS EnKF DA results with 20 members are better than all the other methods including AFWA SNODEP, operational GFS/GDAS product, LIS control run, and LIS DA with direct replacement.

International NWP and hydrological models use snow depth observations from WMO synoptic stations, which however have a relatively coarse spatial coverage. Making available extra snow measurements from national high-resolution weather networks into the WMO GTS (Global Telecommunication System) and WIS (WMO Information System) would thus be very valuable since in situ observations from SYNOP and other national stations network constitute a reliable information to initialise weather prediction systems. They are provided in near real-time on the GTS for numerical weather prediction applications. In the presentation by de Rosnay et al. the status of current available in situ data was shown and gaps of snow depth reporting on the GTS were discussed in relation to ongoing actions, conducted in the context of both the World Meteorological Organization Global Cryosphere Watch (GCW) SnowWatch initiative and the Harmosnow COST action. These initiatives contribute to improve snow depth reports availability on the GTS. ECMWF's snow analysis assimilates the Interactive Multi-Sensor Snow and Ice Mapping System (IMS) snow cover information, in addition to the snow depth measurements. A set of Observing System Experiments (OSEs) conducted to evaluate the relative impact of different types of observations to analyse snow depth showed that forecasts of both surface fields and low-level atmospheric variables are highly sensitive to the snow initialisation. Combined assimilation of both types of observations, in situ snow depth and IMS snow cover, significantly improves near surface weather parameter forecasts compared to experiments without snow data assimilation or experiments using partial snow observing system.

Hydrological models use snow observations directly or indirectly in order to deliver and improve flood forecasting and water management planning. Snow melt runoff predictions provide valuable information for hydropower reservoir management in regions dominated by snow. The forecasting skill may be improved by adjusting the initial snow storage in the models by assimilation of in situ and satellite based snow observations. However, in many situations the uncertainties in initial conditions are less important compared to the uncertainties in the seasonal meteorological forecast used to force the hydrological model.

The objective of the study of Gustafsson et al. is thus to make a systematic evaluation of the improvement in seasonal spring melt forecast skill by assimilation of various types of snow data - in situ observations and/or satellite remote sensing data for a number of hydropower reservoir basins in Sweden representing different amount of snow domination. Data assimilation methods such as Ensemble Kalman filter was used to update the simulated water storages in snow and soil during the initialization period before forecast issued at different times through the winter and melt season. Different methods for updating hydrological models were evaluated 1) use of operational snow depth measurements from SMHI, 2) satellite based data on snow water equivalent and snow cover area from EU FP7 project CryoLand, and 3) pre-operational manual observations of snow depth, snow density and snow water equivalent located close to hydropower reservoirs in the Swedish mountain area, operated by hydropower management company Vattenregleringsföretagen AB. Results showed that assimilation of snow information improved spring melt forecasts in most of the study areas and study years. It was mainly manual observations of snow water equivalent and satellite based data on fractional snow cover area that where useful for improving the forecasts. However, it was shown that model updating with snow data does not always lead to improved simulations of river discharge and reservoir inflow probably due to: 1) the uncertainty in the weather forecast/climatological forecast is more important than the uncertainty in the snow conditions at the start of the forecast, 2) the updating methods do not take into account systematic representation errors in the assimilated snow information in an adequate way, and 3) the manual snow observations are most sparse and the satellite based data is most uncertain in the mountain areas that are most interesting for spring melt runoff predictions from a hydropower management perspective.

The uncertainty in model physics of snow processes in relation to the initial state of limited-area NWP forecasts addressed Kuzmina et al. in the presentation of the SNOWE-technology. Since wrong initialization of snow water equivalent (SWE) and snow depth (SD) in NWP runs can lead to screen-level temperature errors of more than 10 K, a reliable initial state on regions with sparse measurements is needed. The approach is to use SYNOP snow depth observations together with satellite snow mask for correction of SWE values from global data assimilation systems at local scale with a stand-alone system. The aim is to obtain more realistic daily SWE values at the location of the SYNOP station, since the history of previous weather situations is taken into account. This product of reliable SWE has shown a positive impact in limited area COSMO forecasts and can be used in hydrological forecasts. SNOWE technology as corrector of initial fields of COSMO-Ru have reduced RMSE of T2m forecasts near snow boundary in the spring time on 0.5–1.5 K, in some places up to 7 K. The data of SNOWE technology (fields of SWE values) have been applied in the spring flood time in 2015/2016 for northeast part of Russian Federation, where the observing network is rare and the pre-operational runs of SNOWE in COSMO-Ru technology have demonstrated more realistic values of SWE than obtained from global NWP data assimilation system (in comparison with direct hydrological snow measurements) for winters 2014/2015 and 2015/2016.

# Snow observations and evaluation

During the last decades, instrumentation and measurement techniques, especially remote sensing, have advanced fast, providing significant amount of new information about the extent and properties of snow. On the other hand, the description of the varying snow cover has improved in NWP, climate and hydrological models. Furthermore, advanced data assimilation (DA) methods are being developed to combine the improved observations with the improved models. However, in situ measurements from SYNOP ground stations are indispensable for the assimilation of the snow depth at that location. Global NWP models assimilate SYNOP snow measurements from different national ground station networks which provide measurement data on the GTS. The presentation from M. Lange showed that a monitoring of SYNOP station snow depth reports is mandatory to detect problems in the snow analysis related to SYNOP reports which could have a disadventageous impact on the NWP forecast.

Taking into account the increasing amount of new information about the extent and properties of snow, the presentation by E. Kourzeneva addressed the existing gap between rapidly developing remote sensing snow observations and simple methods to assimilate them into NWP models. The main problem to assimilate remote sensing Snow Extent (SE) observations is that SE is a categorical variable (yes/no), and statistical methods are not yet developed for such a type of data. There is no understanding how to represent qualitatively the observational error of SE, and the impact of observations dominates since there are no objective statistical methods to combine observations from different satellites. A comparison of SE observations from two satellites (METEOSAT and METOP), with SYNOP data and with simulations by the NWP model HARMONIE, showed a good overall agreement between all data sources suitable for data assimilation perspectives. However, all types of data have errors that need to be accounted for in data assimilation systems. Satellite data mainly overestimate snow due to cloud contamination; they may also contain “not detected snow” situations. METOP may give an “added value” to products from METEOSAT, especially for Nordic countries, so it is worth combining them. Some idea about the observational error of categorical SE data is brought from the comparison of SE from two satellites.

Already since the 1970s, passive microwave and multispectral satellite images of the land surface and since the 1990s active microwave sensors are used to detect snow-covered surfaces and parameters such as water content or snow depth. The available sensor types (multispectral, active and passive microwave systems) for the detection of snow from space are taking into account different physical characteristics of the snow pack. An overview of the spectral properties of snow and their consideration in remote sensing retrievals was given by R. Müller et al. with the focus on LSA-SAF (Siljamo et al., 2011) and IMS, (Ramsay ,1998), snow cover products. Different snow cover update options has been discussed. While the spectral behavior of snow and clouds differ, clouds covering land-surface areas with snow for a long time remain a problem for daily and intra-daily updates of the remote sensing products.

The presentation by J. Trentmann et al. covered the evaluation of satellite-based snow coverage information with surface observations. The discrimination of clouds and snow-covered surfaces from satellite measurements is challenging. In particular in climatological time series of remote sensing data, snow coverage is often wrongly classified as clouds and resulting in a systematic underestimation of the derived surface radiation in snow covered situations. Due to the limited spectral resolution of the early satellite sensors the separation of snow cover and clouds often is not possible from historic remote sensing data using current retrieval algorithms, which require multi-spectral information. Using consecutive satellite images (visible channel only) from geostationary satellites and modern image recognition software it is possible to separate clouds from snow coverage by analyzing motion vectors. It was shown that the application of these modern algorithms allows the retrieval of snow coverage from historical Meteosat data despite their limited spectral information. This approach has the potential to generate a consistent and homogeneous 33 year daily time series of snow coverage that could be used, e.g. in reanalysis applications.

Blowing snow has an impact on the surface mass balance of a snowpack and ice sheet by transport and sublimation that is recognized of importance for large-scale snow and ice-covered regions like Antarctica.
Snowdrift events detection is possible using satellite data (Palm et al., 2011). The near-surface blowing snow layers are apparent in lidar backscatter profiles (532 nm attenuated backscatter) and enable snowdrift events detection. These data are processed from CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), at a high resolution (1x1 km digital elevation model extending from 40 km altitude to below sea level). However, the satellite detection of blowing snow events is limited to layers of a minimal thickness of 20-30 m. In addition, thick clouds, mostly occurring during winter storms, can impede drifting snow detection from satellite products.
For this reason, a new algorithm was developed by A.Gossart, designed to detect blowing snow from ground-based remote sensing ceilometer at Princess Elisabeth station (Dronning Maud Land, East Antarctica, 72°S 23°E). The 910 nm attenuated backscatter profiles at 15 s temporal resolution are processed with this algorithm and strong blowing snow signal from layers thicker than 15 m could be detected for the first time with this approach.
The added value of the newly developed algorithm is that it detects blowing snow events mixed with snowfall, thus during overcast conditions. Those events are missed out by the satellite detection, but represent the majority of the blowing snow events at the Princess Elisabeth station.

# Snow observations and physical snow models

In mountainous regions, the knowledge of evolving snow pack properties is a key factor for various application fields, such as water resource management, road maintenance, winter tourism and predicting the risk of avalanches. Information about the current snow pack and the atmospheric state, respectively, is essential in snow forecasting, since numerical snow models are blended with meteorological input data to provide an accurate estimate of the actual snow cover state (analysis), which should best fit available observations. If no model errors are taken into account (so-called perfect model assumption), poor short-term forecasts of snow models are caused by errors in the analysis that is used as the initial condition for a subsequent forecast of snow variables. Thus, it can be expected that on average, additional observations should improve the analysis especially in data sparse regions, where the information for estimating snow cover is insufficient. In the presented study of R. Koch and M. Olefs, maps of the daily fractional snow covered area product from the Moderate Resolution Imaging Spectroradiometer (MODIS) during the winter season of 2015-2016 are used to correct modeled quantities (snow depth, snow water equivalent) of a very high resolution, distributed and operational snow cover model (SNOWGRID) over Austria. When MODIS data are available, the snow cover fraction for this model time step is taken into account in determining whether or not snow is present in the modeled SNOWGRID fields. As a measure for the impact of MODIS observations on the modeled snow quantities differences between model runs with and without the use of MODIS for correcting SNOWGRID fields are analyzed. Taken into the account the uncertainties in satellite data for mountainous regions the aim of the qualitative and quantitative comparison is to gain a further understanding of possible improvements in the SNOWGRID forecast skill by using remote sensing data from the moderate-resolution satellite observations in model domains which include areas of low elevation together with regions of high elevation.

The presentation of U. Böhm et al. focused on the combination of ground-based measurements with remote sensing snow observations within the grid-based physical model SNOW4 for analysis and short-term forecast of snow cover accumulation and depletion. During the winter season SNOW4 is employed operationally every 6 hours to generate up to 72-hours forecasts of water supply being the total amount of runoff from snow melt and precipitation for flood warning and forecasting. To provide suitable initial conditions, in the analysis phase of the past 30 hours, hourly surface measurements of 2m-temperature, wet bulb temperature, wind speed, sunshine duration and precipitation are forcing the model. Ground-based daily snow observations at 06 UTC are interpolated to the model grid once a day including a quality control. The differences to the model state are computed using a global approach and a set of various indicators. In case a certain threshold is exceeded, the model is adjusted towards the gridded observations. In the used interpolation algorithm, a method based upon Optimal Interpolation by Gandin (1963) is applied. First, a Trend Surface Analysis as an equivalent to Universal Kriging is performed. This is followed by the Optimal Interpolation procedure. Similar to External Drift Kriging, remote-sensing data may supplementary be used to estimate the spatial structure of the snow cover in regions with sparse or no surface observations. It was found that the use of satellite observations as a supplementary source of information has a positive impact on the result of the gridding algorithm of ground observations, validation activities are ongoing. IMS data provide an added value compared to Land-SAF data in terms of coverage due to a multi-senor approach. For operational use in SNOW4, a selection-based approach will be implemented (use of IMS product, if available, otherwise, use of LAND-SAF product). A remaining problem is the frequency of data provision and how to update the daily IMS product sub-daily.

# Snow observations and hydrological models

The presentation by M. Bartík and T. Šatala considered snow observations forested mountainous regions, where remote sensing data from space show large uncertainties. This study shows that main factors influencing SWE in forest are vegetation type and state, altitude, and exposition. Differences in SWE and snow depth have been analysed for several winter seasons using open forest area, open meadow area, living forest and dead forest. It was found that snow depth and SWE for dead forests are higher than for living forest, but the snow density does not change significantly. The comparison of snow accumulation and melting in the living and dead forest revealed that the snow cover was more stable in the living forest. The consideration of vegetation effects on snow could improve forecast of water supply in catchment areas with forests.

The presentation by M. Osuch et al. focused on the development of a hydrological model defining the arctic catchment response to observed recent changes in weather and climate. The study was carried out for small unglaciated catchment Fuglebekken, located in the vicinity of the Polish Polar Station Hornsund on Spitsbergen. Within two hydrological years 2013-2014 and 2014-2015 a number of hydro-meteorological measurements were conducted. These measurements include the snow cover depth, snow water equivalent, air temperature and precipitation. During the ablation season outflow was measured with 10 minutes interval by portable device Nivus PCM F with active Doppler sensor. For hydrological modelling the conceptual rainfall-runoff HBV model was used. The model was calibrated and validated for each year independently. Model calibration together with an estimation of parametric uncertainty was carried out using the SCEM-UA algorithm (Shuffled Complex Evolution Metropolis). In addition, an analysis of the influence of data time step on the obtained results of calibration and validation was performed. That effect was examined through a numerical experiment where the HBV was calibrated with data of different temporal resolution: 10, 20, 30, 40, 60, 90 minutes, 2, 3, 6, 12 and 24 hours. The relationships between model parameters and time step, as well as influence of time step on the calibration and validation results were tested (Wawrzyniak et al. 2018). The outcomes indicate that the results of calibration depend on the data time step and also data averaging. Good results of calibration and validation were obtained, which allow the use of the model in other years and gives the opportunity to assess the actual state, as well as simulate future changes.
Considering changes in seasonality of snow cover, air temperature and precipitation in western Spitsbergen by M. Osuch and T. Wawrzyniak focused on the analysis of the variability of daily snow cover depth, air temperature and precipitation using the newly proposed tool ‘Moving Average over Shifting Horizon (MASH)’ (Anghileri et al. 2014), the identification of changes in seasonality with statistical change detection test, a comparison of the estimated trends between stations, and an analysis of potential sources of changes in air temperature and precipitation. Time series from 32 snow seasons between 1984 and 2016 at four stations in Spitsbergen were processed with the MASH approach together with a trend analysis of the filtered data by the Mann-Kendall method. With this method, differences in snow depth, precipitation and temperature between stations were found and potential sources of changes, i.e. sea ice extent (SIE), North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Scandinavia pattern (SCE), Polar/Eurasia pattern (POL), East-Atlantic pattern (EA), East Atlantic/West Russia pattern (EA/WR) have been analysed. It was shown that the MASH method combined with the Mann-Kendall test can be successfully applied for trend estimation in daily snow cover depth, air temperature and precipitation (Osuch and Wawrzyniak 2017, 2018). Since the available in-situ measurements of snow depth in Spitsbergen are rare and data are available from a few sites, problems with homogeneity of the data still exist and further investigations and snowpack modelling are required to explain the differences in observations at the Hornsund station.

# Summary

The workshop showed the valuable collaboration between research and operational services in the use of snow observations for data assimilation in numerical weather prediction models, hydrological models, and physical snow models. In these applications common objectives, methods, and challenges exist to combine in situ and satellite data for usage in a model and for validation. For data assimilation systems there is a demand for more combined products retrievals and flow dependent approaches but on the long term the aim is the assimilation of radiances.

Current snow data products from satellite are typically based on the unique spectral properties of snow. They are used to force land-surface models within a data assimilation framework. However, snow cover and fractional snow cover still dominates the used remote sensing data, while satellite products for snow water equivalent and snow depth have not such a broad application in operational models. A topic of current research is to combine one retrieval product, e.g. snow cover from different satellites in a data assimilation system. New approaches are investigated to open up early satellite images for long-term records in reanalysis applications.

In situ measurements provide an essential data source of snow depth. Their sparse coverage in some regions is however problematic. Especially in mountainous areas, where satellite data, which are also influenced by clouds and snow below vegetation (e.g., forest) have large uncertainties due to varying snow conditions on very short distances, in situ snow measurements provide valuable additional information. Therefore it is important to improve the snow depth reports availability on the GTS, as supported by WMO GCW and COST Harmosnow. Since satellite data have great advantages in regions with only few in situ measurements compared to interpolated station data, the great potential of a combined assimilation of both types of observations, in situ snow depth and remote sensing data (e.g., IMS snow cover), was discussed during the workshop, since results demonstrated the significant improvement of near surface weather parameter forecasts using this method.

With the SNOWE technology at SYNOP stations an approach that considers the history of the snow pack for initialisation of limited areas NWP forecasts is available in the operational COSMO NWP consortium. For hydrological models the assimilation of snow information improves spring melt forecasts and in these models manual observations of snow water equivalent and satellite based data on fractional snow cover area are considered as mainly useful. The sensitivity of these model results to data time step and averaging of data is investigated using long-term measurements.

Existing problems in snow analysis products related to data assimilation methods were discussed. For example, snow water equivalent increments that correct the model trajectory to compensate for snow melting processes issues, result in a water budget that is potentially disadvantageous for hydrological forecasts. A combined snow and soil moisture data assimilation can be useful to keep consistency in the water budget. Since observation errors are important in snow data assimilation the relationship between MODIS snow product errors and temperature have been discussed according to J. Dong et al., 2014.

The interaction processes between vegetation and snow are important to capture in models since large areas with seasonal snow in northern hemisphere are regions with forests. Depending on vegetation type and state, altitude, exposition snow depth and snow water equivalent can differ significantly with implications for hydrological forecasts. For climatological applications the investigation of the seasonality of snow is important together with an analysis of potential sources of change in snow depth. Improved models could help to explain the existing differences in snow observations at remote sites.

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