9th EARSeL Workshop on Land Ice and Snow

Remote Sensing of the Cryosphere
Monitoring what is vanishing

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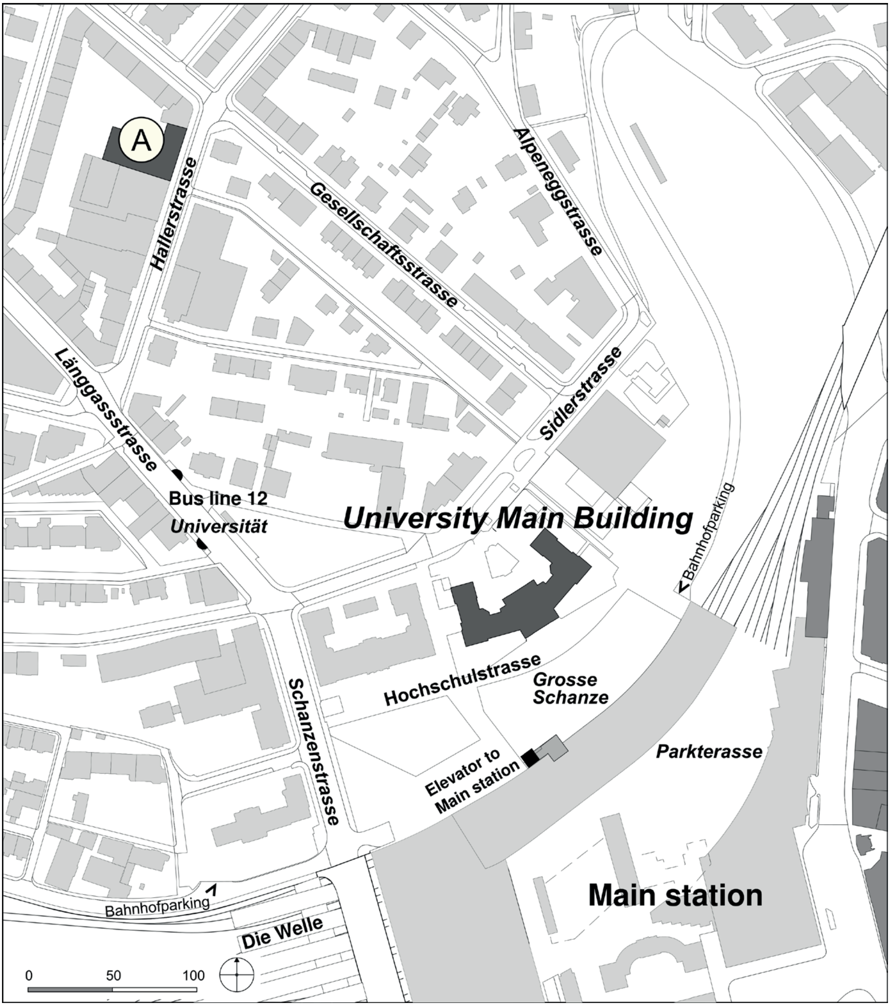
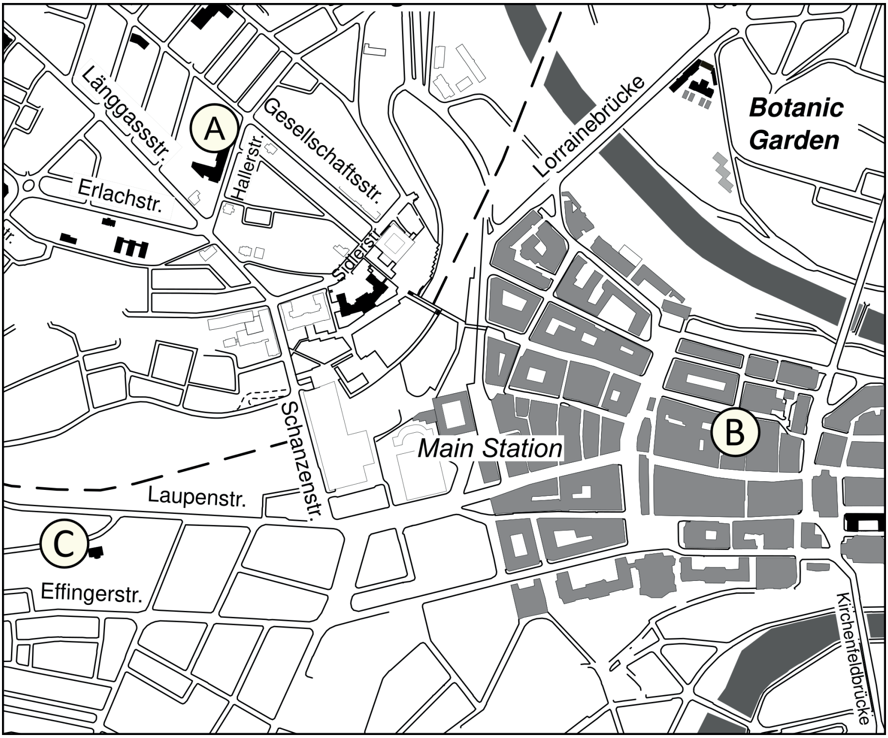
Location (Conference venue)



A: Institute of Geography, Hallerstrasse 12, 3012 Bern

Location (Conference dinner and Ice breaker)



A: Institute of Geography, Hallerstrasse 12, 3012 Bern

B: Restaurant zum Äusseren Stand (Conference Dinner),
Zeughausgasse 17, 3011 Bern

C: Haus der Universität (Ice breaker reception),
Schlösslistrasse 5, 3012 Bern

Coastal Sea Ice in the Beaufort Sea Region from CCRS MODIS Composites Products Since 2000

Alexander Trishchenko, Calin Ungureanu, Junhua Li, Dustin Whalen, Vladimir Kostylev, Yi Luo
Canada Centre for Remote Sensing, NRCan, Canada

Coastal zone ice (or landfast ice) is a very important phenomenon that affects coastline dynamics, the near-shore ecosystems and human activities. Quantitative information about the distribution of coastal zone ice is required to better understand the impacts associated with climatic changes in the Arctic region. In this study, we utilized 10-day, monthly and seasonal composite maps derived at the Canada Centre for Remote Sensing (CCRS) from Moderate Resolution Imaging Spectroradiometer (MODIS) at 250m spatial resolution. CCRS generates these products at the national scale since 2000. Subset of these data records over the Beaufort Sea area has been analysed. The coastal ice regime in this area is generally driven by the seasonal cycle of meteorological conditions, the bathymetry of the ocean floor in the shallow water zone, and by the Beaufort Gyre (large-scale ocean circulation system persistent over the region). Delineation of coastal zone ice has been based on the mean and standard deviation of MODIS reflectance maps combined with seasonal snow/ice probability maps. An analysis of multiannual variability of the spatial extent and timing of the coastal ice conditions will be presented. Comparison of CCRS MODIS results with the Canadian Ice Service (CIS) ice charts, the National Snow and Ice Data Center (NSIDC) data, and local observations will be also discussed.

Our analysis showed the presence of some systematic negative (positive) trends in the ice (ice-free) multi-year time series and their correlation with the regional air temperatures at the surface despite substantial year-to-year variations.

This work is supported through the NRCan Climate Change Geoscience Program and the CCRS project on Long-Term Satellite Data Records.

Is it Cloud or Snow? – Influence of Cloud Retrieval on AVHRR GAC Snow Records

Helga Weber, Martin Stengel, Kathrin Naegeli, Stefan Wunderle, Rainer Hollmann
University of Bern, Switzerland

Snow and clouds are both highly dynamic climate variables, which affect the evolution of Earth's climate. Both variables are critical indicators to understand and predict the climate and are defined as Essential Climate Variables (ECVs, see e.g. the recent Implementation Plan by GCOS (GCOS-200, 2016). Continental to global datasets for these ECVs are primarily derived by remote sensing sensors to strengthen the observational component for a better understanding of their role in the climate system. Recently, Global Area Coverage (GAC) data of the heritage Advanced Very High Resolution Radiometer (AVHRR) have been employed to compose global, observational datasets of the above mentioned ECVs (e.g. EUMETSAT CM SAF, ESA Cloud_cci, ESA Snow_cci).

Here, we systematically assess the influence of clouds on snow detection, since the accurate distinction of clouds (and fog) from snow and ice cover is problematic due to similar shortwave albedos. Our study is focused on Europe and we use AVHRR Local Area Coverage (LAC) data of the University of Bern to analyze the impact of the onboard AVHRR GAC data resampling scheme on the detection of clouds and snow. Due to the onboard resampling AVHRR GAC data are reduced from the original 1.1 km2 footprint size at nadir AVHRR LAC images by averaging four out of five neighboring pixels of every third scanline resulting in an effective footprint size of 1.1 x 4.4 km with a sampling size of 4 km. So far, no quantification exists for the loss of information on cloud detection due to the on-board resampling and the associated influence of clouds on snow detection. To guarantee comparability we simulate AVHRR GAC from AVHRR LAC data from recent NOAA and MetOp satellites (i.e. N-18, MO-A, N-19, MO-B). These simulated data will be used to calculate statistics of the frequency of occurrence for individual channels (i.e. CH1, CH2, CH3A/B, CH4), cloud features and snow cover used for cloud and snow detection. In a further analysis, a direct comparison of the simple cloud masks created from AVHRR LAC data and with Cloud_cci AVHRR-AM/PMv3 cloud detection (incl. probability maps, Stengel et al., 2019 in review) and preliminary snow masks from the Snow_cci project is planned.

GCOS-200, 2016: The Global Observing System for Climate: Implementation Needs. GCOS-200 (GCOS-214). World Meteorological Organization (Lead by Alan Belward, JRC, Italy), p. 316.Stengel,

Stengel, M. et al. 2019: Cloud_cci AVHRR-PM dataset version 3: 35 year climatology of global cloud and radiation properties, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2019-104, in review, 2019.

The Copernicus Global Land Service Lake Ice Extent Product For Northern Hemisphere

Anna-Maaria Kirsikka Heinilä, Olli-Pekka Mattila, Sari Metsämäki, Kari Luojus, Gabriele Schwaizer, Thomas Nagler, Burak Simsek, Joanna Ossowska
Finnish Environment Institute, Finland

Lake ice has strong effect on earth energy balance and local weather by hampering the energy exchange between water and atmosphere. In many areas over Northern latitudes lake ice plays an important role to citizens as a means of transportation and recreation. Additionally, lake ice extent is a sensitive climate change indicator.

Lake Ice Extent (LIE) is one of the Copernicus Global Land Service (CGLS) near-real-time (NRT) products. The Global Land Service is a component of the Copernicus Land service that provides a series of bio-geophysical products on the status and evolution of land surface at global scale at mid and low spatial resolution. Finnish Environment Institute (SYKE), Finnish Meteorological Institute and ENVEO IT GmbH are part of the cryosphere team providing snow and lake ice related products for CGLS. The new product in the portfolio will be the Northern Hemisphere Lake Ice Extent product in 500m resolution (LIE-NH). SYKE has developed a new method to assess LIE using optical Sentinel-3 Land Surface Temperature Radiometer (SLSTR) data. The algorithm is based on multidimensional distributions calculated for training data using several reflectance/ thermal bands and indices. The work was supported by optical high resolution images. The classification is provided in three categories: i) open water, ii) ice cover and iii) cloud. To provide accurate lake ice extent information an accurate watermask plays an important role. The watermask has been generated using the 25 meter resolution water occurrence data provided by European Commission's Joint Research Centre, UN Environment and Google. The LIE-NH products will be spatially extensively validated during autumn 2019 using high resolution Sentinel-2 Multispectral Instrument (MSI) and SYKEs unique in-situ datasets.

In this presentation we will introduce NRT LIE-NH product, explain protocol for LIE-NH product validation using high resolution satellite data and in-situ data and show results from validation.

Seasonal Snow Melt Season Timing In Northern Hemisphere From 1982 to 2015 Derived From CLARA-A2 SAL Data

Kati Anttila, Terhikki Manninen, Emmihenna Jääskeläinen, Aku Riihelä, Panu Lahtinen
Finnish Meteorological Institute, Finland

In the changing climate the cryosphere is reacting rapidly to the atmospheric changes. The seasonal snow coverage and albedo affect the global energy budget. In this study we look at the timing of the melt season in the Northern Hemisphere between 40°N and 80°N land areas. The study is based on the The CM SAF Cloud, Albedo And Surface Radiation dataset from AVHRR data surface albedo data record (CLARA-A2 SAL) which is produced in the Satellite Application Facility on Climate Monitoring (CM SAF), funded by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The data record is based on optical satellite data and covers the years from 1982 to 2015. The data is presented in 0.25° resolution. We analyze the annual variation of the five day mean surface albedo values at each location separately. The drop in the spring time albedo from snow covered to snow free condition are used to define the start day, end day and length of the melt season (Anttila et al 2018). We present the observed changes in these from 1982 to 2015, look at the possible drivers for these and analyze the spatial and temporal differences in the extreme values for melt season timing.

Anttila, K., Manninen, T., Jaaskelainen, E., Riihela, A., & Lahtinen, P. (2018). The Role of Climate and Land Use in the Changes in Surface Albedo Prior to Snow Melt and the Timing of Melt Season of Seasonal Snow in Northern Land Areas of 40°N–80°N during 1982–2015. Remote Sensing, 10(10), 1619, https://doi.org/10.3390/rs10101619

Impact Of Snow Cover Data Assimilation Over The Tibetan Plateau On Medium Range Numerical Weather Prediction

Patricia de Rosenay, Gianpaolo Balsamo, Yvan Orsolini, Emanuel Dutra, Boqi Liu, Retish Senan, Wenli Wang, Martin Wegmann, Kun Yang, Congwen Zhu
ECMWF, United Kingdom

In this paper we investigate the sensitivity of the European Centre for Medium-range Weather Forecasts (ECMWF) Numerical Weather Prediction (NWP) system to the assimilation IMS snow data assimilation over the High Tibetan Plateau (HTP). A control experiment is conducted, consistent with the current operational NWP system configuration, where the IMS snow cover used in areas with altitudes under 1500m, excluding high mountains. A sensitivity experiment is conducted with IMS snow cover data assimilation at all altitude, including high mountains. Both experiments are conducted for medium-range weather prediction from September 2011 to December 2012. Results show that assimilating IMS snow cover over the HTP dramatically improves snow depth over the HTP area by reducing the large positive bias in snow depth in the ECMWF model in this region. Reduced snow depth over the HTP results in warmer surface conditions, reduced albedo and increased surface roughness. These changes in the surface conditions over the HTP propagate to larger scales by shifting northward the Asian jet stream circulation, leading to a global scale impact of IMS snow cover data assimilation over the HTP. Results and impact on surface conditions and medium-range NWP are presented and discussed.

Multisensor Approach For Fractional Snow Cover And Snow Water Equivalent Retrievals

Sari Johanna Metsämäki, Kari Luojus, Matias Takala, Jouni Pulliainen, Mwaba Hiltunen, Kirsikka Heinilä, Gabriele Schwaizer, Thomas Nagler
Finnish Environment Institute, Finland

A lot of effort has been recently put on the development and evaluation of regional or NH scale snow products. Algorithm development, product intercomparison and validation have been carried out in several projects, for instance ESA SnowPEx, EU Copernicus GlobLand and ESA CCI Snow. Typically, the addressed variables are Fractional snow cover (FSC) and Snow Water Equivalent (SWE).

The SWE retrievals by passive microwave radiometer (PMWR) data are hampered by the inhomogeneity of snow layer, e.g. after several freeze/melt processes and snow wetness. Optical and NIR sensors – although also sensitive to snow characteristics, are able to provide information on FSC. The combined use of these data sources, aiming at better snow mapping, has already been successfully tested, but more information is needed to gain optimal results. Some recent prototype GlobSnow SWE Climate Data Records (CDR) use optical data-based binary snow extent data for the fusion i.e. to correct the SWE according to optical data-based snow information (by JAXA; Hori et al., 2017). However, using FSC instead of binary data is expected to give more accurate results as in general binary snow information does not provide information on snow patchiness. In principle, SWE retrieval is designed for areas fully covered by snow (FSC=100%) and therefore would benefit from FSC-information instead of binary snow/non-snow data. We will therefore employ also JAXA FSC to its feasibility for SWE improvement. In addition, since there are also other optical sensors enabling FSC-estimation than those utilized in JaXa time series (e.g. SNPP VIIRS and Sentinel-3 SLSTR), we investigate and demonstrate the possible discrepancies between them. This is carried out by i) comparing the FSC products from EU Copernicus GlobLand and ESA GlobSnow NRT service and ii) comparing the reflectance data at selected relevant wavelength bands of the two above mentioned sensors. The gained results will benefit the future data fusion for improved SWE for instance allowing their parallel use, which can maximize the number of clear-sky pixels in the fusion.

Climate models e.g. ECHAM5 use modelled SWE to obtain FSC (Raisanen et al., 2014). With the dataset on FSC and SWE we collect here, we are able to detect how well this conversion agrees with the EO-retrievals of FSC and SWE. This information is valuable for the development of climate models. In this work, independent SWE-retrievals (i.e. without data fusion) that are provided by GlobSnow SWE CDR are employed. The investigated time periods cover January-May of 2018 and 2019.References:Hori, M., et al. 2017. A 38-year (1978–2015) Northern Hemisphere daily snow cover extent product derived using consistent objective criteria from satellite-borne optical sensors.

Hori, M., et al. 2017. A 38-year (1978–2015) Northern Hemisphere daily snow cover extent product derived using consistent objective criteria from satellite-borne optical sensors. Remote Sens. Environ., 191, 402-418.

Räisänen, P., Luomaranta, A., Järvinen, H., Takala, M., Jylhä, K., Bulygina, O. N., Luojus, K., Riihelä, A., Laaksonen, A., Koskinen, J., and Pulliainen, J.: Evaluation of North Eurasian snow-off dates in the ECHAM5.4 atmospheric general circulation model, Geosci. Model Dev., 7, 3037–3057, https://doi.org/10.5194/gmd-7-3037-2014, 2014.

Advancements of Snow Cover Monitoring Based on Synergy of Sentinel-1 SAR and Sentinel-3 SLSTR

Thomas Nagler, Helmut Rott, Joanna Ossowska, Gabriele Schwaizer, Eirik Malnes, David Small, Kari Luojus, Sari Metsämäki, Lars Keuris, Simon Pinnock

ENVEO IT GmbH, Austria

TThe synergistic use of data from different satellites of the Sentinel series offers excellent capabilities for generating advanced products on parameters of the global climate system and environment. A key parameter for climate monitoring, hydrology and water management is the seasonal snow cover. In the frame of the ESA project SEOM S1-4-SCI Snow, led by ENVEO, we developed, implemented and tested a novel approach for mapping the total extent and melting areas of the seasonal snow cover by synergistically exploiting Sentinel-1 SAR and Sentinel-3 SLSTR data and apply this for the Pan-European domain.

Data of the Copernicus Sentinel-1 mission, operating over land surfaces in Interferometric Wide Swath (IW) mode at co- and cross-polarizations, are used for mapping the extent of snowmelt areas applying change detection algorithms. In order to select an optimum procedure for retrieval of snowmelt area, we conducted round-robin experiments for various algorithms over different snow environments, including high mountain areas in the Alps and in Scandinavia, as well as lowland areas in Central Europe covered by grassland, agricultural plots, and forests. In mountain areas the tests show good agreement between snow extent products during the melting period derived from SAR data and from Sentinel-2 and Landsat-8 data. In lowlands ambiguities may arise from temporal changes in backscatter related to soil moisture and agricultural activities. Dense forest cover is a major obstacle for snow detection by SAR because the surface is masked by the canopy layer. Therefore, areas with dense forest cover are masked out. Based on the results of the round-robin tests we selected for the retrieval of snowmelt area a change-detection algorithm using dual-polarized backscatter data of S1 IW acquisitions over land. The algorithm applies multi-channel speckle filtering and data fusion procedures for exploiting VV- and VH-polarized multi-temporal ratio images. The binary SAR snowmelt extent product at 100 m grid size is combined with the Sentinel-3 SLSTR snow product in order to obtain combined maps of total snow area and melting snow. Complementary to the melt snow extent from SAR, the optical satellite images provide information on snow extent irrespective of melting state, but are impaired by cloud cover. For generating a fractional snow extent product from Sentinel-3 SLSTR data we apply multi-spectral algorithms for cloud screening, the discrimination of snow free and snow covered regions and the retrieval of fractional snow area extent.

Exploring the Recent Developments in Snow Cover Mapping by Machine Learning Algorithms

Semih Kuter, Zuhal Akyurek
Cankiri Karatekin University, Turkey

Declared as an essential climate variable, spatial extent of snow cover plays a significant role in most of the hydrological, meteorological and environmental processes. This talk aims to introduce the recent results of our efforts in snow cover mapping by machine learning algorithms. In the first part, we present the experimental design considerations and the outcomes for fractional snow cover (FSC) estimation from MODIS data over European Alps by artificial neural networks (ANN), multivariate adaptive regression splines (MARS) and support vector regression (SVR) methods. The dataset used in this part comprises 20 MODIS - Landsat 8 image pairs acquired between Apr 2013 and Dec 2016. The results indicate that the agreement between the reference FSC maps derived from higher resolution Landsat 8 binary snow maps and the ANN, MARS and SVR models is quite satisfactory with average R ≈ 0.93, whereas MODIS' own product MOD10A1 (C5) exhibits slightly poorer performance with R ≈ 0.88. The second part of the talk introduces the implementation of multi-response MARS approach for supervised pixel-based classification on Sentinel 2 images with cloud and snow cover. Three Sentinel 2 images taken on northeastern part of Turkey in December 2017, March and April 2018 are used as image dataset. Five general class labels are assigned as response: cloud, ice, land, snow and cloud. The performance of MARS is also compared to that of maximum likelihood (ML) method using basic accuracy metrics derived from the corresponding error matrices. The classified images are also visually assessed with regard to some challenging issues frequently encountered on scenes with cloud and snow cover such as cloud-snow discrimination and mislabeling of pixels at the land-snow boundary. Multi-response MARS overperforms ML algorithm on all three images with higher Kappa values (MARS: 0.87, 0.82 and 1.00; ML: 0.74, 0.71 and 0.86, on December 2017, March and April 2018 images, respectively). Visual analysis reveal that MARS has a distinctive advantage in correctly labeling the pixels at the edges of land-snow boundary. The overall results illustrate the ability of nonparametric machine learning algorithms in successfully resolving complex and high dimensional dependencies in multispectral datasets and their potential for the retrieval of snow cover data from remotely-sensed imagery.

Analysis Of Backscatter Timeseries For Cryospheric Applications

Gwendolyn Dasser, Hendrik Wulf, David Small
University of Zurich, Switzerland

The understanding of the spatiotemporal behaviour of snow cover enables informed decisions on water resource management, risk assessment and hydroelectric power production. Information on snow cover plays an important role in weather and climate research. In this study, we work toward improving the identification of wet snow areas using Local Resolution Weighting (LRW) composites with high spatial temporal resolution created from Sentinel-1A and -1B Radiometrically Terrain Corrected (RTC) backscatter products. For a test site in the Bernese Alps, composites acquired within periods ranging from 36 hours to twelve days are used to generate wet snow maps. These are compared with external reference information (optical imagery, gridded temperature records) over the range of two years. For validation of the radar composites, optical datasets co-registered spatially and temporally, are based on a variety of optical sensors to minimize differences between radar and optical acquisition times. This combination of datasets allows us to test new approaches for generating an optimal dry-winter reference image used in the process of SAR wet snow detection. Benefits as well as limitations of current LRW composites are discussed, when validating the algorithm‘s performance in dependence of prevalent land cover classes. Current methods for wet snow detection using SAR are applied and their performances reviewed. Information gained on the behaviour of snow cover at a regional scale (~10^5 km^2) will eventually be applied to the analysis of a timeseries consisting of twelve-day composites featuring the Swiss Alps. This approach allows for a detailed methodological validation before its application to larger areas.

Physically Based Cloud Gap Filling Of Satellite Snow Products

Johanna Nemec, Gabriele Schwaizer, Thomas Nagler, Michael Aspetsberger
ENVEO IT GmbH, Austria

Daily regional to global snow extent products from medium optical resolution sensors are input to many applications in water management, hydrology, meteorology and climate monitoring. The snow extent products are based on mature algorithms for estimating fractional snow extent and for detection of cloud covered areas. According to the international snow product evaluation and intercomparison project SnowPEx the accuracy of the snow products has been assessed showing an overall agreement of about 8 to 15% with reference data depending on the surface type and environment. Clouds have been identified as one of the major drawbacks of optical sensors for snow monitoring as clouds mask large parts of the earth's surface and cloud / snow discrimination is still a major source of errors in snow products from optical satellite data. There are various concepts proposed and used to provide snow information for pixels detected as clouds in daily snow products including the use of snow information from passive microwave sensors (currently available only with much coarser spatial resolution) or from SAR images (sensitive only to wet snow, but no separation of dry snow and snow free conditions). Another approach simply uses the most recent observed snow extent for one pixel as long as it is cloud covered and just increasing the uncertainty in time. In this presentation we propose a physically based approach by assimilating satellite snow products with a snow pack model running for each pixel separately. As starting point we use a time series of satellite based snow products providing at least one observation of fractional snow cover per pixel. For every pixel we set up a one-layer snow pack model driven by high resolution numerical meteorological data interpolated to the grid of the snow product. If a pixel is detected as cloud covered, we convert fractional snow extent into average snow mass and run the snow pack model using meteorological data (temperature, precipitation) as input using as statistical function. The estimated snow mass for the pixel is converted to fractional snow extent to fill the cloud covered pixel. The approach has been tested and validated for the Alps and Pan-European domain using CryoLand / GlobLand snow products with 500 m resolution and using Copernicus Atmosphere Monitoring Service and the NCEP Global Forecast System as input. In this presentation we will explain the concept of the cloud gap filling approach, show time series of the cloud gap filled product and will present results of the extensive validation of the cloud cap filled products.

Development of a Snow Monitoring System for EUMETSAT EPS-SG / METimage

Thomas Nagler, Gabriele Schwaizer, Sari Metsämäki, Lars Keuris, Helmut Rott, Bojan Bojkov
ENVEO IT GmbH, Austria

The area extent of the seasonal snow cover is a key parameter for a wide range of applications in meteorology, hydrology, water management, ecology, climate monitoring, and global change research. Observations of snow-cover extent from visible and infrared sensors, operating on polar-orbiting and geostationary satellites, have been widely used during the last decades. The different data sets vary in spatial resolution, repeat coverage and performance. The medium resolution optical sensor METimage onboard of the upcoming second generation EUMETSAT Polar System (EPS-SG) satellites will offer excellent new capabilities for operational monitoring the seasonal snow pack at medium-scale spatial resolution. METimage is a passive cross-track scanning imaging spectroradiometer measuring reflected solar and emitted terrestrial radiation in the visible and infrared spectral domain between 0.443 and 13.345 µm with spatial sampling of 0.25, 0.5 and 1.0 km at s.s.p. over a swath width of about 2800 km. Complementary to the advancement by METimage on its own, the synergistic use of METimage and Copernicus Sentinel-3 SLSTR data will offer the basis for further progress in generating consistent, high quality, long-term data sets on snow cover extent from regional to global scale.

In the EUMETSAT project Snow Cover / Extent Demonstrator for Optical Sensors (SEDOS) a snow retrieval algorithm is developed for METimage following an iterative cycle comprising algorithm development, implementation as prototype software, the generation of test products and the evaluation of the algorithm performance. Current multispectral algorithms for estimating fractional snow are adapted to exploit the advanced spectral capabilities of METImage. In order to match the needs for different applications in meteorology and hydrology, viewable snow extent and canopy corrected snow extent (snow on ground) products are derived. An important issue for the quality of snow extent products is the discrimination of clouds and snow covered areas. New multispectral algorithms are currently in development making use of the full spectral capabilities of METImage. In order to test the performance of the prototype snow processor we use Sentinel-3 SLSTR and OLCI data co-registered at 500 m pixel spacing, covering the PanEuropean domain. The snow extent product is validated using snow products from high resolution optical satellite data and in-situ data. The added value of this product will be assessed by intercomparison with medium resolution snow products from other sources. In this presentation we will introduce the capabilities of METImage for snow monitoring and report on the status of algorithms for fractional snow cover retrieval and cloud screening, show comparisons with currently available operational snow products, and present examples of PanEuropean snow products that are based on synergy of SLSTR and OLCI data. A concept for combining METImage with geostationary FCI data onboard of upcoming Meteosat Third Generation (MTG) geostationary satellites for snow cover monitoring will be presented.

Accuracy Study Of Snow Cover Maps Based On AVHRR Data With Different Spatial Resolution

Soumita Patra, Kathrin Naegeli, Stefan Wunderle
Birla Institute of Technology, University of Bern, Switzerland

Snow cover is one of the most dynamic geophysical parameters which can be monitored by satellite remote sensing. It influences hydrological processes, water management, snow-melt runoff, and economy. Moreover, snow cover changes the albedo of the earth surface and thus strongly impacts the earth radiation balance and climatic changes over longer time scales. The precise monitoring of the spatial and temporal variability of snow cover is thus crucial to understand seasonal to inter-annual variability and changes in the Earth system.

The Advanced Very High Resolution Radiometer (AVHRR) provides a unique opportunity to retrieve a long time series of more than 35 years to study surface properties at a global scale and on a daily basis. AVHRR data is available in two different spatial resolutions: 1) Global Area Coverage (GAC) with 4.4 km2 2) Local Area Coverage (LAC) with 1.1 km2 at nadir. LAC data is mainly used for regional applications due to its limited spatial availability. To the best of our knowledge, the differences in seasonal snow cover maps occurring due to different resolution from both LAC and GAC data has not yet been investigated. In the present study, we thus make a novel comparison and in-depth assessment of differences and similarities of retrieved winter snow cover maps from AVHRR LAC and GAC data, focusing on the different topography and land cover types of European Alps, aiming at estimating the accuracy of GAC snow cover maps for the European Alpine environment.

Here, we present preliminary results of the comparative assessment of LAC and GAC snow cover products. Pixel-wise fractional snow cover maps are obtained by using the Normalised Difference Snow Index (NDSI) in combination with other band thresholds. The percentage of total seasonal snow covered area and statistical parameters like standard deviation is calculated for both data sets to assess the accuracy of the AVHRR GAC snow maps. To asses the influence of topography and landcover over snow cover area, we retrieved elevation, slope, and aspect in different classes of the alpine mountain region and evaluate the relationship with snow cover area. Moreover, we calculate categorical statistics of probability of detection, and false alarm rate. A series of two winters is used to address the research aim in the regional context of the European Alps. This comparison of snow products based on LAC and GAC data shows their individual assets, points out discrepancies and highlights crucial information to be considered for the derivation of a consistent fundamental climate data record (FCDR). Finally, our results will add extra value to the generation of AVHRR derived long term snow cover products and with that support our understanding of climatic changes related to snow cover on the European Alps.

Potentials of Advanced Microwave Scanning Radiometer 2 (AMSR2) Brightness Temperature for Improving Snow Depth Retrieval in Sweden

Jie Zhang, Veijo Pohjola, Rickard Pettersson
Uppsala University, Sweden

Passive microwave remote sensing has proved an effective approach for monitoring snow depth and has been widely used for large-scale monitoring. The Advanced Microwave Scanning Radiometer 2 (AMSR2) onboard the Global Change Observation Mission 1-Water (GCOM-W1) is featured by multi-frequency and dual-polarization channels with improved spatial resolution and provides more potentials for describing snow depth as compared to others. Currently, a global AMSR2 snow depth product is available; however, the algorithm is developed based on global data without a good representation of Sweden and may not be suitable for Sweden. As a basis for the development of an improved regional snow depth product in Sweden, this work first intends to explore the potentials of AMSR2 brightness temperature at different frequencies and polarizations for describing snow depth during the snow seasons, using the meteorological sites all over Sweden. The capabilities of both single-channel brightness temperature (BT) and dual-channel brightness temperature difference (BTD) of any two frequencies and polarizations are investigated to depict the snow depth for each site, using the entire AMSR2 time series available from 2012. The performances of different BT/BTD combinations are revealed for each site, the distribution of the BT/BTD performances are explored across space, and the brightness temperature channels or channel combinations most sensitive to snow depth are identified. Those selected brightness temperature features, together with other factors (e.g., geographic location, terrain, land cover and so on) will be combined to help propose an enhanced snow depth retrieval/ downscaling algorithm and thus develop an enhanced snow depth product in Sweden. This work aims to better characterize the snow depth in Sweden from space with improved accuracy and at higher spatial resolution.

EUMETSAT HSAF SNOW COVER PRODUCTS: 10 Years On

Zuhal Akyurek, Ali Nadir Arslan, Kenan Bolat, Simone Gabellani, Silvia Puca, Burak Simsek, Semih Kuter, Matias Takala, Alexander Toniazzo
METU, Turkey

Reliable snow cover extent is of vital importance in order to have a comprehensive understanding for present and future climate, hydrological, and ecological dynamics. Development of methodologies to obtain reliable snow cover information by means of optical and microwave remote sensing (RS) has long been one of the most active research topics of the RS community. The H-SAF was established by the EUMETSAT Council on 3 July 2005; since then from development to operational phases several snow prodcucts have been disseminated. In this study EUMETSAT snow cover products namely H10, H34, H12, H35 and H13 are presented.

H10 and H34 are daily operational products of snow extent generated from the visible (VIS) and infrared (IR) radiometry of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument on Meteosat Second Generation (MSG) satellites. The high temporal resolution and wide aerial coverage of SEVIRI imagery make it highly suitable for snow-cover mapping. Indeed, the daily snow cover product is derived for a multi-temporal analysis of SEVIRI 15-min images, that are processed as new data are available to collect the largest possible number of cloud-free pixels. The resulting daily map having 5km spatial resolution consists of four different classes: snow, cloud, water and bare land. H10 snow product has a spatial coverage delimited between longitude 25_ W–45_ E and latitude 25_–75_ N and H34 has full disc coverage.

H12 and H35 products are generated from METOP-AVHRR and have 0.01° spatial resolution. The effective snow cover generation employs visible and shortwave near infrared data. The algorithm for flat/forest areas assumes that in optical wave¬lengths, the observed reflectance from a target is a sum of surface scattering from ground layer and volume scattering from forest canopy layer. The algorithm for mountainous areas is based on a sub-pixel reflectance model.

H13 is the product obtained from microwave sensors namely SSMI/S and they have 0.25° spatial resolution. H13 retrieval is based on snow depth algorithm based on 19H and 37H microwave channels. H13 algorithm uses the Helsinki University of Technology (HUT) snow emission model having slightly changes in the assimilation for flat/forest and mountainous areas.

Validation studies indicate the optical snow products have large snow mapping accuracy with respect to ground snow observations, which varies between 69 and 94% in the winter seasons. Recent studies of H13 product give RMSE as 40 mm for flat areas and 45 mm for mountainous areas for annual snow season. In this talk the validation results presented by several studies (Piazzi et al., 20191; Surer et al., 2014; Surer et al., 2012) are discussed in detail.

Supraglacial Hydrology at 79°N Glacier, Greenland – Lessons learned and Challen-ges

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Surface melt in north-east Greenland provides a substantial amount of mobile water and it has to be expected that this is going to increase in future, as climate projections show even for moderate RCP2.6 scenarios a strong increase in temperature in the north-east of Greenland. Surface melt will thus also become a major factor in the contribution of the ice sheet to sea level rise via various processes, of which most are not or poorly represented in ice sheet modelling. This work aims at providing an observational basis for conceptual model development.

The main pathways of melt water are percolation into the firn (forming melt layers at depth), surface run-off via rivers of variable size and length and the aggregation in supraglacial lakes. A high number of supraglacial lakes is freezing over during winter. The onset of melt can be detected well with Sentinel-1, allowing to retrieve time series of surface melt extent using the backscatter. Using polarimetry, we developed also time series of lake evolution. Both approaches will be presented here. What remains a challenge is the water content of firn from remote sensing data, as well as quantifying the amount of run-off. However, using optical data from Sentinel-2, the evolution of surface run-off can be studied qualitatively at an even higher resolution and can be used for supporting conceptual model development.

In addition to satellite remote sensing, AWI's new ultra-wide band (UWB) snow radar has been flown over this area during cold conditions. This data is currently analyzed with respect to the structure of the upper 10m of the glacier, of which we will present preliminary results.

Greenland Ice Sheet Surface Albedo And Optical Properties From The Sentinel-3 OLCI Instrument

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The Greenland ice sheet mass loss is a key contributor to the accelerating sea level rise. The ice sheet mass loss occurs as meltwater runoff and solid ice discharge at marine terminating glaciers. Surface melt is the origin of the former and speeds up the latter. Snow and ice surface characteristics and their albedo determine how much solar energy is absorbed and used for melting. The launch of Sentinel-3A in February 2016 and Sentinel-3B in April 2018 allow the determination of these surface conditions at an unprecedented level of accuracy. Using a combination of analytical and empirical methods validated against ground measurements, we document the surface albedo variations in the three mid-season periods since 2017, including the high-melt summer of 2019. We present the timing, magnitude and spatial distribution of the summer albedo decline on the Greenland ice sheet and detail their causes: grain size variations, water content and ice algae growth.

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A Comparative View Into Trends In Arctic Cryosphere's Surface Albedo During 1982-2015; Sea Ice, Seasonal Snow, And The Greenland Ice Sheet

Aku Riihelä, Kati Anttila, Terhikki Manninen
FMI, Finland

The increasing melt of the Northern Hemisphere's cryosphere during the past decades has resulted in the shrinking of its snow and ice cover, and has also left its mark on the remaining snow and ice as reduced surface albedo. However, different parts of the Arctic exhibit different spatiotemporal variability in the albedo reductions, and are driven by different atmospheric and surface processes.

Here, we propose to provide a spatiotemporally resolved three-decade overview into the surface albedo evolution of the three principal components of the Arctic cryosphere: the sea ice cover of the Arctic Ocean, the North American and Eurasian seasonal snow cover, and the Greenland Ice Sheet. The analysis covers 1982-2015 and is principally based on the CLARA-A2 surface albedo dataset from the CM SAF project, based on an intercalibrated radiance record from the AVHRR series of optical imagers. For comparison purposes, snow & ice surface albedo data from e.g. the MODIS-based MOD10A1 and combined AVHRR-MODIS GLASS datasets are also included to assess trend consistency.

These surface albedo changes and trends will be considered in the context of their primary drivers as proposed in literature (e.g. atmospheric ridging over Greenland), and intercompared to assess covariability. All trend calculations include uncertainty considerations and statistical significance testing to identify robust trends from natural interannual variability.

Albedo of the cryosphere from Sentinel-3

Jason Box, Baptiste Vandecrux, Alex Kokhanovsky, Kenneth Mankoff
GEUS, Denmark

For much of the pre-melt and melt season, sunlight absorption can be the dominant melt energy source for snow and ice on land, glaciers, sea, and lakes. Snow and ice melt feedbacks play a role in Arctic amplification of climate warming.

The Copernicus ESA Sentinel-3 A and B platforms host two sensors with optical bands: the Ocean Land Color Instrument (OLCI) and the Sea and Land Surface Temperature Radiometer (SLSTR).

We show OLCI and SLSTR data can be used to produce optical products (chiefly albedo but also snow surface grain diameter and specific surface area) at high accuracy. This presentation presents algorithms, validation, products and a near real-time processing chain.

The albedo product used in data assimilation efforts will be presented.Albedo, an essential climate variable (ECV) along with snow cover (also designated an ECV) may be unified now that the Sentinel-3 mission carries the torch after a very impressive and long (20 year) performance of the NASA MODIS sensor. The overlap with MODIS now spanning three years means we can bridge snow albedo to provide a climate scale measurement of snow albedo, a unified ECV.

Surface Roughness Effect on Snow Albedo

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The albedo is one of the Essential Climate Variables (ECV) and the albedo of snow is especially important, because snow has the highest albedo of surface materials and also its variation range is large. In order to derive the albedo of snow reliably from satellite data, one has to have a large number of satellite retrievals of diverse azimuth directions (like AVHRR data for the SAL product of CM SAF) or has to be able to accurately model the relationship between the directional reflectance and hemispherical albedo of snow. The snowpack is usually modelled as an isotropic scattering volume characterized by the specific surface area of the scattering elements, i.e. snow grains. Taking into account that the snow density is very low compared to the density of the snow grains and they are not densely packed with respect to the wavelength range in question of optical satellites, the assumption of a cloud of randomly located scatterers is reasonable. Then the incidence angle of individual rays hitting (assumed) spherical scatterers constitutes a Gaussian distribution centered around the nominal incidence angle value. However, when the surface of the snowpack is clearly anisotropic or the surface roughness is significant, the assumption of a volume of randomly located scatterers may no more be valid and the incidence angle distribution may deviate markedly from the Gaussian distribution constituted by the a random volume of identical scatterers. The effect of surface roughness properties (amplitude and phase) on incidence angle distributions are analyzed theoretically using cosine functions to demonstrate the effect of various kinds of surface roughness. In addition, measured surface roughness and grain size values are used as input for the calculations to get realistic effect of the surface roughness on albedo. The SNORTEX campaigns 2009 and 2010 produced hundreds of surface roughness profiles of various new and old snow in varying weather conditions. They have been analyzed using ray tracing and the results show that the surface albedo can be 10 % lower for rough than even snow surfaces.

Modeling the Evolution of the Structural Anisotropy of Snow

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The structural anisotropy of snow results from a spatially anisotropic distribution of the snow microstructure. Because of the anisotropic structure, microwave signals are differently delayed depending on their polarization. Radar systems which can measure polarimetric phase differences allow therefore for an estimation of the structural anisotropy of snow from ground and from space.

Up to now, no model exists to calculate the structural anisotropy, despite the fact that the structural anisotropy is a key parameter for improving parameterizations of physical properties of snow. To enable the use of the anisotropy in snowpack models as internal variable, we propose simple rate-equation to model the temporal evolution of the anisotropy. The proposed model includes two effects, namely temperature gradient metamorphism and settling, and can be forced by any snowpack model that predicts temperature and density. The model is validated with a comprehensive set of anisotropy measurements from X-ray computer tomography (CT) and radar measurements. After validation of the proposed effect of temperature gradient metamorphism with CT time-series from lab experiments, we use SNOWPACK simulations to calibrate the model against radar time-series from the NOSREX campaigns in Sodankylä, Finland. Finally we validate the simulated anisotropy profiles with field-measured full-depth CT profiles.

Our results confirm that the creation of vertical structures is mainly controlled by the recrystallization rate of water vapor. Our results further indicate a yet undocumented effect of settling on the creation of horizontal structures. Overall the model is able to reproduce the characteristic anisotropy variations in time series of 4 different winter seasons with a very limited set of calibration parameters.

Apart from improving the parametrization of physical snow properties like the thermal conductivity, mechanical properties, or the permittivity, the gained knowledge of the anisotropy evolution improves the interpretation and modeling of microwave observations of snow and allows to use them e.g. for the detection of new snow fall or to characterize the growth dynamics of depth hoar from space.

Improvement Of The Snow Albedo Retrieval Combining Optical And Microwave Sensors: Ground-based Observations From The SnowAPP Campaign (Sodankylä, Finland)

Roberta Pirazzini, Petri Räisänen, Juha Lemmetyinen, Terhikki Manninen, Teruo Aoki, Ghislain Picard, Jouni Peltoniemi, Martin Schneebeli, Marco Pasian, Masashi Niwano, Henna-Reetta Hannula, Kati Anttila, Anna Kontu, Leena Leppänen, Pedro Fidel Espin Lopez, Amy Macfarlane, Outi Meinander, Ines Olivier, Teijo Arponen, Jonas Svensson, Jianwei Yang, Lorenzo Silvestri, Aleksi Rimali, Laurent Arnaud
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The ambitious goal of the SnowAPP project is to develop a unified model for the snow microstructure and its interaction with the electromagnetic radiation in the optical (i.e. solar) and microwave regions, based on a comprehensive dataset collected in field campaigns in Sodankylä, Finland (March- April 2019, March-April 2020). Using this model, we will build a method to retrieve snow albedo from the combination of optical and microwave radiances, improving the present-day optical-based methods that are limited to cloud-free conditions and suffer from large uncertainties at the low solar elevation angles typical of high latitudes.

Snow microstructure determines the mechanical, thermodynamic, and radiative properties of the snow, and it is therefore needed to calculate the snow albedo using forward optical radiative transfer models. The penetration of radiation to the snowpack depends on the wavelength, and consequently, observations made in different wavelength regions yield information on snow microstructure at different depths. Furthermore, the scattering cross section depends differently on snow microstructure in the optical and microwave regions. In the framework of the SnowAPP project, we will attempt to identify and test a relationship between measurements of microwave radiances and optical radiances, using co-located ground-based measurements of spectral albedo, high frequency microwave response, and detailed snow properties. Moreover, as the snow surface roughness and snowpack anisotropy affect the snow surface reflectivity in both wavelength domains, we will attempt to measure and parameterize also their effect.

This presentation illustrates the measurements collected during the first year of the snowAPP campaign, which aim to monitor the snow evolution from the dry to the melt season. The automatic observations include snow spectral and broadband albedo from the visible through the near-infrared wavelengths, as well as snow backscatter at 1-9 GHz frequencies and brightness temperature at 89 and 150 GHz frequencies. The manual snow pit observations conducted once or twice a day include vertical profiles of snow temperature, density, snow specific surface area, liquid water content, resistance force to penetration, macro-photography of snow crystals, and snow stratigraphy. In addition, snow samples for snow impurity content and micro-tomography analyses are collected, and snow surface roughness is monitored (with automatic and manual methods).

Semantic Earth Observation Data Cube as New Access to AVHRR Data for Land Ice and Snow Cover Monitoring

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This work presents a semantic Earth observation data cube containing a semantically-enriched time-series of AVHRR imagery. A semantic EO data cube is a spatio-temporal data cube containing EO data, where for each observation at least one nominal (i.e., categorical) interpretation is available and can be queried in the same instance. (Augustin et al 2019). Providing analysis ready data (i.e., calibrated and orthorectified AVHRR data) in a data cube along with semantic enrichment reduces barriers to conducting spatial analysis through time based on user-defined AOIs and improves data access by enabling queries of image content instead of being limited to querying data based on when they were acquired and the area covered.

To the best of our knowledge, this is the first EO data cube based on semantically-enriched AVHRR data and has the potential to open the AVHRR archive to a wider audience. This implementation utilises daily observations covering Western and Central Europe acquired between ca. 1200 and 1400 UTC by NOAA-19 starting September 2014 through May 2015 and information derived from them. The data have been calibrated and orthorectified by the Remote Sensing Research Group at the University of Bern and semantically-enriched using the Satellite Image Automatic Mapper (SIAM). SIAM applies a fully automated, spectral rule-based routine based on a physical-model to assign spectral profiles to colour names with known semantic associations; no user parameters are required, and the result is application-independent (Baraldi et al. 2010; Baraldi et al. 2018). Existing cloud masks generated by the Remote Sensing Research Group are also included in the semantic EO data cube as additional data-derived information to support spatio-temporal semantic queries.

Data cube technologies are a game changer for how EO data are stored and accessed, but more importantly in how they establish reproducible analytical environments for queries and information production. An EO data cube in this context is understood as a multi-dimensional array that organises gridded (i.e. raster) data in three dimensions: latitude, longitude and time. The semantic EO data cube and associated Jupyter notebook environment for analysis are created on the fly using a Docker-based solution. This solution containerises implementation, making it scalable to large amounts of data and essentially independent of the user's operating system. Given data and semantic enrichment prepared for a data cube, this solution automates indexing data and ingesting them (i.e. optimising storage and access for a given purpose) to the data cube. This means that anyone with access to the same data can generate an identical data cube for analysis. On the flip side, multiple users can access the same existing data cube as the basis for their own analysis, as well as efforts to reproduce previously generated results. Queries of the semantic EO data cube and related analysis are conducted and documented using Python in Jupyter notebooks, improving transparency and reproducibility of analysis and results. The utility of the semantically-enabled AVHRR data cube is demonstrated based on example queries of snow cover on user-defined AOIs and timespans. However, this implementation is intended to facilitate ad hoc, flexible information generation from data in multiple application domains.

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Photogrammetric Snow Depth Mapping: How good can we get?

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Snow depth and the amount of water stored in the snowpack are key parameters for a wide range of applications such as snow avalanche mitigation, hydropower generation, and ecological questions. Despite its key importance, snow depth in operational settings remains only sparsely measured at point locations (e.g., automated weather stations and observers), thus missing the high spatial variability of the snowpack, and therefore considerably limiting its significance.

Due to the low contrast of snow-covered terrain, photogrammetry was originally not trusted to produce meaningful surface models on snow covered terrain. However, recent studies proofed the ability of photogrammetry to map spatially continuous snow depth over large regions with very high spatial resolution. In the Dischma valley, close to Davos, Switzerland, we simultaneously acquired photogrammetric datasets from the ground (variable spatial resolution), with Unmanned Aerial Systems (3 cm resolution), an airplane (10 cm resolution) and with very high-resolution satellites (30 and 50 cm resolution). Reference snow depth measurements were acquired by manual probing and by fixedly installed snow poles. This unique dataset allows us to compare the resulting photogrammetric surface models, to quantify their performance for snow depth mapping, and to discuss the specific advantages and disadvantages of the different platforms. This is a crucial step to pave the way for remotely sensed measurements as an economic and accurate method to capture the crucial spatial variability of snow depth.

Wide Band Scatterometer Measurements of Alpine Snow

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The multi-year ESA SnowLab project has been carried out at the newly established Davos-Laret test site (Switzerland) from 2016 until 2019. Before, a one season campaign at Gerstenegg (Switzerland) was conducted.

SnowLab provides a comprehensive multi-frequency, multi-polarisation, multi-temporal data set of active microwave measurements over snow-covered grounds in an Alpine snow regime. The main instrument in ESA SnowLab was ESA's SnowScat X- to Ku-band coherent tomographic scatterometer for the 2015-2018 campaigns and WBScat for the 2018/19 campaign. The active microwave measurements are complemented by micro meteorological measurements and regular snow characterization using state-of-the-art sensors, in order to allow resolving the 3D snow microstructure necessary to investigate the origin of electromagnetic signatures associated with scattering effects. The resulting data set is needed to further investigate the relationship between effective snow and ground parameters and their specific microwave backscatter, measured by radars. In addition to traditional backscatter signature measurements, SnowScat/WBScat was used to acquired tomographic and vertical snowpack measurements. All 4 campaigns can be considered highly successful. More than 1800 signature scans were conducted and more than 500 tomographic profiles collected. Near real-time processing and data visualisation supported the monitoring and quality control of the running campaign.

In our presentation we will discuss the main findings and present the lessons learned during the 4 years of field work.

Internationally Coordinated Glacier Monitoring: From Early Warning Indicators Towards Memorials Of The Climate Crisis

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The systematic monitoring of glaciers, distinct from the Greenland and Antarctic ice sheets, has been internationally coordinated for 125 years. The main motivation was origin from – at that time – recently established ice age theories: it was hoped that long-term observations of glacier fluctuations would provide insight into the relevance of regional versus extra-terrestrial forcings. Since then, the goals of international glacier monitoring have evolved and multiplied. Glacier changes in mass have become well recognized as a high-confidence indicator of climate change. It is now clear that humans are both the primary cause and will bear the greatest negative impact of glacier melt. Today, the World Glacier Monitoring Service (www.wgms.ch) receives in-situ measurements of glacier changes in length, volume, and mass from 40 countries and several hundreds of principal investigators. In addition, remote sensing allows to compile information on regional glacier distribution and changes at a worldwide scale. Recent assessments based on these unprecedented datasets show that glaciers globally have lost more than 9,000 Gigatonnes (1 Gt = 1,000,000,000,000 kg) of ice since 1960. This corresponds to a layer of ice covering all of Switzerland to a depth of 250 meters. The melting of this ice alone has raised global sea level by 27 millimeters. Long-term observations and numerous modelling studies provide evidence that current mass-loss rates are historically unprecedented on a global scale, and they indicate that several mountain ranges such as the European Alps, the Caucasus, western Canada, and the Tropics could lose the vast majority of their glaciers within this century. Observers around the globe are reporting the disintegration and complete vanishing of glaciers. Long-term monitoring programs have to be abandoned and – if possible – moved to bigger glaciers with larger elevation extents. In several countries, commemoration ceremonies and memorial sites have recently been established to document the extinction of glaciers for current and future generations.

Comparing Automated Classifications of Snow on Glaciers Based on Sentinel-2 Imagery

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An automated classification of snow cover on glaciers using optical satellite imagery would help to constrain near-real time mass balance estimates. Especially the automation process is challenging though: different acquisition conditions including shadows, clouds and rapidly varying glacier surface topographies make processing without human intervention difficult. Consequently, there have not been many attempts to fully automate the workflow yet. In this study, we apply and extend two already existing workflows to Sentinel-2 data and validate their classification results over Switzerland.

To do this, we develop an Open Source Python tool called "SnowIceSen". It automates image availability checks for a given time and glacier, downloads the data, performs terrain correction, and excludes debris and cloud-covered areas. After that, snow and ice are distinguished by using (1) the ASMAG algorithm (Automated Snow Mapping on Glaciers) by Rastner et al. (2019), (2) a method presented in Naegeli et al. (2019), and (3) an alternate version of the latter introducing more flexible parameters. For validation purposes, we use a manually digitized set of 430 snow lines for the summer months of 2015-2018. Evaluation is done using Cohen's Kappa (K), a statistic ranging from -1 (worst value) to +1 (best value). We find that high snow cover and high cloud cover result in a poor agreement ($K < 0.2$). However, for cloud-free scenes with medium snow cover, both the ASMAG algorithm and the alternate version of the Naegeli method can reliably predict the on-ice snow cover distribution ($0.6 < K < 0.9$). Furthermore, we compare the equilibrium line altitude retrieved from in-situ measurements to the highest transient snow line altitude found during summer. The values agree within 10 meters. The processing of individual scenes, however, can be challenging: small contrasts between snow and ice reflectance, erroneous cloud cover detection, as well as terrain and cloud induced shadows can prevent a correct classification. In the future, rule-based classifiers might enhance algorithm performance.

Region-wide Estimate Of Annual Glacier Mass Balance For The Tien Shan And Pamir From 2000 To 2018.

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University of Fribourg, Switzerland

The Tien Shan and Pamir host more than 25000 glaciers. They act as important freshwater resources for Central Asia. The contribution of glacier melt to the total river runoff is expected to reduce significantly under ongoing climate change. Most region-wide glacier mass balance assessments focus on decadal changes. Only a few studies address seasonal or annual variability.

With this study, we aim to infer seasonal to annual mass balances for all glaciers larger than 2 km2 of the Tien Shan and Pamir from 2000 to 2018. We use an accumulation and temperature-index melt model closely constrained with repeated transient snowlines for each year and glacier individually. The snowline mapping is carried out automatically based on surface reflectance data of Landsat satellite scenes. Thereby, we derive spatially distributed shortwave broadband albedo for the glacierised area of each image to discriminate between snow-covered and bare-ice surfaces.

In a second step, we constrain the modelled decadal mass balances with glacier-specific geodetic mass balances, using ASTER digital elevation models (DEMs). Additionally, we use high-resolution DEMs (High Mountain Asia DEMs) for DEM differencing and select sensor specific pairs, based on at least five years of separation, and with at least 40% scenes overlap.

First results from transient snowline-constrained modelling combined with geodetic surveys confirmed a decadal mass loss of −0.36 ± 0.32 to −0.44 to ± 0.32 m w.e. yr-1 for 2000 to 2017 for the subranges Kyrgyz Ala-Too (Tien Shan), the Pamir-Alay (Pamir) and the Akshiirak range (Tien Shan). Lower rates of mass loss are encountered for the early years of the study period. Our results show a significant trend towards increased mass loss for the Pamir-Alay and the Kyrgyz Ala-Too, accompanied with a moderate increase of the interannual variability with time. Annual variability is similar for the Kyrgyz Ala-Too and Pamir-Alay and is considerably smaller for the Akshiirak massif.

Our time series, annually tied to transient snowline observations and linked to the geodetic estimates at the decadal scale, enable the analysis of yearly mass balance variability for glaciers in a region with few in situ measurements. Moreover, they deliver important baseline data for in-depth analysis of the spatio-temporal glacier response to climate change and the importance of glacier melt contribution to the total river runoff at an enhanced temporal resolution.

Investigation and estimation of penetration-related TanDEM-X elevation bias – A study over the Greenland Ice Sheet

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Ongoing global warming causes dramatic changes worldwide. Rapid retreat of glaciers and ice sheets has been observed within the past decades, leading to significant consequences at a global scale. In order to understand and predict these complex processes and their impacts, detailed and area-wide information on the environment's response to climatic changes is required. Interferometric Synthetic Aperture Radar (InSAR) systems are well suited as they provide 3-d information at high spatial resolution over large areas without limitations due to weather conditions and illumination. Especially the TanDEM-X mission is of high interest since it provides elevation data with an unpreceded spatial resolution of 0.4 arc seconds without accuracy limitations caused by repeat-pass interferometry. However, penetration of the SAR signal into snow and ice induces an elevation bias depending on the acquisition geometry as well as the snow and ice characteristics. In this context, the current study aims to develop an easy-transferable pixel-based approach for X-band penetration-related elevation bias estimation in order to provide accurate digital elevation data for the assessment of glaciers and ice sheets. In particular, the penetration bias estimation is performed using a multiple linear regression model based on single-pass interferometric coherence and backscatter intensity independently of prior knowledge on the physical properties of the snow pack. TanDEM-X RawDEM products from April 2012 and IceBridge laser-altimeter measurements acquired in a period from 30 March 2012 to 16 May 2012 at two test sites on the Northern Greenland Ice Sheet are used for model development and accuracy assessment. In addition, the transferability of the proposed approach regarding acquisition geometry and acquisition time is discussed. Validation efforts shows good agreement between predictions and observations with a coefficient of determination of R^2= 68 % and an RMSE of 0.68 m. The results indicate inter-annual variations in penetration-related elevation bias, which must be taken into account for glaciological applications such as altimetric mass balance techniques. Finally, the study demonstrates the benefit of X-band penetration bias estimation in the application context of ice sheet elevation change detection.

The Potential Of Low-Cost UAVs And Open-Source Photogrammetry Software For High-Resolution Monitoring Of Alpine Glaciers: Kanderfirn (Swiss Alps)

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Unmanned Aerial Vehicles (UAV) are a rapidly evolving tool in geosciences and are increasingly deployed for studying the dynamic processes of the earth's surface. To assess the potential of autonomous low-cost UAVs for the mapping and monitoring of alpine glaciers, we conducted multiple aerial surveys on the Kanderfirn in the Swiss Alps in 2017, 2018 and 2019 using open hardware and software of the Paparazzi UAV project. The open-source photogrammetry software OpenDroneMap was tested for the generation of high-resolution orthophotos and digital surface models (DSMs) from aerial imagery and cross-checked with the well-established proprietary software Pix4D. Accurately measured ground control points served for the determination of the geometric accuracy of the orthophotos and DSMs. A horizontal (xy) accuracy of 0.7–1.2 m and a vertical (z) accuracy of 0.7–2.1 m was achieved for OpenDroneMap, compared to a xy-accuracy of 0.3–0.5 m and a z-accuracy of 0.4–0.5 m obtained for Pix4D. Based on the analysis and comparison of different orthophotos and DSMs, surface elevation, roughness and brightness changes from 3 June to 29 September 2018 were quantified. While the brightness of the glacier surface decreased linearly over the ablation season, the surface roughness increased. The mean DSM-based elevation change across the glacier tongue was 8 m, overestimating the measured melting and surface lowering at the installed ablation stakes by about 1.5 m. The presented results highlight that self-built fixed-wing UAVs in tandem with open-source photogrammetry software are an affordable alternative to commercial remote-sensing platforms and proprietary software. The applied low-cost approach also provides great potential for other regions and geoscientific disciplines.

Estimation of Regional to Global Snow Depth using AMSR2 Observations and SMSA

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The Satellite-based Microwave Snow Algorithm (SMSA) is an algorithm used to estimate snow depth and snow water equivalent (SWE) from space by coupling microwave simulations from the Dense Media Radiative Transfer (DMRT) model with observations from JAXA's Advanced Microwave Satellite Radiometer – 2 (AMSR2). The satellite-based algorithm estimates snow temperature, snow grain size and snow density, key variables in the DMRT simulation. These estimates are produced within a modelling framework that requires only AMSR2 observations. By using snow depth as a free variable to minimize the differences between model brightness temperature (Tb) estimates and observed AMSR2 Tbs, an estimate of snow depth can be made. Snow depth estimates from SMSA are compared with in situ measurements of snow depth from the WMO's global surface observations of the day. Daily aggregated error statistics, and station aggregated error statistics are calculated for each season from 2012-13 to 2018-19. Results show the improved performance of the new approach in comparison with the baseline AMSR2 algorithm estimates currently in production at JAXA. The approach cannot estimate accurately mountain snow depths because of the spatial heterogeneity and extreme depth of snow accumulation in these regions relative to the sensitivity of AMSR2 observations. However, for non-mountain landscapes, error statistics indicate that the bias ranges from -3.1 to -0.5 cm (-8.0 to -2.5 cm) globally for SMSA(baseline algorithm) with an RMSE range of between 18 and 20 cm (20.4 to 24.8 cm). Ongoing algorithm improvements are likely to reduce these statistics further. SMSA is an example of a semi-physically based retrieval that is parameterized strictly by passive microwave observations and static ancillary data sets to provide fully independent estimates of snow depth.

Overestimation of MODIS Snow Cover Products and A Solution Method

Chunyu Dong, Lucas Menzel
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MODIS snow cover products have been widely used in hydrological studies. Cloud cover and snow misclassifications are the two major limitations for the hydrological application of MODIS snow data. However, most of the previous research efforts for improving MODIS snow products were paid to cloud removal, and there are few studies concerning the misclassified snow due to cloud/snow confusion. In this study, we developed a multistep algorithm to reduce the overestimation error in MODIS snow data. We applied station-based observations to generate a set of meteorological filters, which were then used to identify falsely classified snow pixels. This algorithm showed high performance in improving accuracy of MODIS snow data and in producing cloud-free snow maps. Finally, we proposed a novel framework for snow mapping and simulations, which highlights the cross-scale integration of in situ and remotely sensed snow measurements and the assimilation of improved remote sensing data into hydrological models.

Regional snow line elevation retrieval using public webcam images

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The elevation of the snow line is an important indicator of snow cover in mountainous regions. It depends on the particular weather conditions and can be used, for example, as an input for hydrological modeling, to monitor climatic behavior, or to reduce gaps caused by cloud cover in satellite-based snow cover retrieval. Snow line estimates from satellite images can be restricted by cloud cover that prevents satellites from capturing snow information on the ground. Terrestrial images offer major advantages during such cloudy phases since they are often located below the cloud cover where their view on the ground is mostly not obscured by clouds. In Switzerland, thousands of publicly accessible webcams are available that can be used for snow cover analyses. These webcam images offer great opportunities to analyze the small-scale variability of the snow line on a high spatio-temporal resolution.

Our study aims at retrieving the regional snow line elevation in the Swiss Alps using webcam-based snow cover maps. In this talk, we first give an overview on the main processing steps required to generate snow cover maps from publicly available webcam images. We analyze mapping accuracies and discuss advantages and limitations of webcam-based snow cover analyses. Finally, we present preliminary results of our regional snow line elevation retrieval.

Global Assessment of Supraglacial Debris-Cover Extents

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Rocky debris on glacier surfaces influences ice melt rates and the response of glaciers to climate change. However, scarce data on the extent and evolution of supraglacial debris cover have so far limited its inclusion in regional to global glacier models. Here we present an approach to automatically map supraglacial debris cover from optical satellite images at a global scale. Our approach makes use of the cloud-computing platform Google Earth Engine (GEE; https:// earthengine.google.com/) and exploits the large number of optical satellite images that are currently available.

In this contribution, we present mapping results from Landsat 8 and Sentinel-2 images, with 30 and 10 m spatial resolution, respectively. In principle, our approach allows rapidly mapping changes in the distribution and extent of debris cover at any time period, for which suitable satellite imagery is available in GEE, such as the Landsat data sets. The goal of this contribution is twofold. First, we present our new automatic mapping approach and evaluate it by comparison with a recently published data set of semiautomatically mapped supraglacial debris cover from the Karakoram and Pamir Mountains. Second, we provide the first global assessment of the spatial distribution of supraglacial debris cover, excluding the Greenland ice sheet and Antarctica, which are mostly free of debris.

We find that about 4.4% (~26,000 km2) of all glacier areas (excluding the Greenland ice sheet and Antarctica) are covered with debris, but that the distribution is heterogeneous. The largest debris-covered areas are located in high-mountain ranges, away from the poles. This likely reflects the fact that glaciers near the equator are exclusively found in high mountain ranges that are typically steep and feature abundant steep rock walls, that is, the source areas of the debris. In regions that are closer to the poles, ice cover increases and topographic elevations decrease to the extent that existing topography may even get buried by ice, hence eliminating any potential source areas for debris.

At a global scale, we find a negative scaling relationship between glacier size and percentage of debris. This observed global scaling of debris-cover fraction with glacier size supports the notion of source areas that get drowned with increasing glacier size. Therefore, the influence of debris cover on glacier mass balances is expected to increase in the future, as glaciers continue to shrink.

Minimum Snow/Ice Cover Extent over Northern Circumpolar Landmass at 250-m Spatial Resolution from MODIS and VIIRS: Climatic Trends and Suitability for Annual Updates of Glacier Inventory since 2000

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Imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) has been processed at the Canada Centre for Remote Sensing (CCRS) to generate the clear-sky mosaics (composites) for the Northern circumpolar zone (9,000 km × 9,000 km) since 2000. The data products spatially consistent with MODIS are also generated from the Visible Infrared Imaging Radiometer Suite (VIIRS) imagery since 2017 to ensure the overlap and continuity of time series in post-MODIS era. Mosaics are produced at 250-m spatial resolution with 10-day intervals (three per month) for seven MODIS land bands B1-B7 and five VIIRS I-bands from the swath (L1 or SDR) imagery using a spatial downscaling technique. The warm season (April-September) snow/ice probability maps and seasonal spectral reflectance aggregates are also produced to characterize the variability of minimum snow/ice (MSI) extent over land, ocean and coastal regions.

20-year time series of the MSI extent are analyzed for the thirteen fist-order geographical regions identified in the Randolph Glacier Inventory (RGI) that overlaps with our study area in the Northern Hemisphere. We compare CCRS-derived year-to-year MSI extent variations with the RGI baseline, and series of land cover maps available the European Space Agency (ESA) Climate Change Initiative (CCI) project. Annual time series of CCRS-derived MSI extent demonstrate good internal consistency and correlation with regional seasonal climate conditions. The CCRS-derived MSI extent agrees reasonably well with the RGI baseline and can be recommended to Glacier Scientific Community, as the first order validation data and the source of annual updates.

This work is supported through the NRCan Climate Change Geoscience Program (CCGP) and the CCRS activity on Long-Term Satellite Data Records (LTSDR) as part of the project “EO Baseline Data for Cumulative Effects”.

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Towards A Unified Estimate Of Mountain Glaciers Contribution To Sea Level Rise since 1975

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Glaciers outside of the ice sheets contributed approximately 1/3 of observed sea level rise since 1971 but estimates remain uncertain due to few observational records prior to the extensive satellite coverage beginning at the turn of the century. The recently declassified images from the reconnaissance satellite series Hexagon (KH-9), that acquired 6 m resolution photographic stereoscopic images from 1971 to 1986, opens new possibilities for historic regional-scale observations of glacier elevation and elevation change. However stereo processing of scanned films presents a unique set of challenges.

Here we present the development of an automated pipeline to generate DEMs at 24 m resolution from scanned KH-9 images. The pipeline includes preprocessing steps to detect fiducial marks and to correct distortions of the film caused by 40-years of storage, is able to automatically solve for camera position and orientation, and optimally aligns to an ancillary DEM for determination of elevation change. We present results obtained over Alaska obtained by comparing historical KH-9 DEMs with modern ArcticDEM topography to reconstruct a 40-year glacier elevation change. Preliminary results yield a total mass change of 1360 Gt or 4.2 mm of sea-level rise over 1975-2015 for the region.

Light Absorbing Impurities In The Olivares Basin, Central Chile

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Light absorbing impurities such as mineral dust, organic material or black carbon can reduce snow and ice albedo. Lowered albedo causes feedback mechanisms that can enhance snow and ice melt. Increased black carbon but also elevated mineral dust concentration have been reported for Central Chile. The glaciers located in the Olivares basin, Chile have lost a substantial amount of mass in recent years in response to atmospheric warming and precipitation reduction. However, little is known about the contribution of light absorbing impurities on snow and ice melt.

This study aims to (1) characterize light absorbing impurities detected in snow and ice samples, (2) quantify albedo based upon satellite imagery and (3) estimate the effect on the ablation processes of the Olivares glaciers. For this purpose, we combined remote sensing results with laboratory and field measurements. Ice and snow samples from 2018 and 2019 are analysed for organic and elemental carbon using a thermal-optical method and for trace element concentrations with inductively coupled plasma optical emission spectrometry. We use x-ray diffractometry and scanning electron microscopy to assess the mineralogical and elemental compositions of the impurities. These impurities are assigned to a reflectance spectrum using hyperspectral imaging microscopy. For each ice sample, the spectral reflectance is measured in-situ using a fieldspectrometer. We compare these measurements with an albedo map from a Landsat 8 scene of close-to-the-same date to extend our small-scale analysis of the spatial albedo distribution to glacier-wide and catchment scale.

We found high concentration of mineral dust (99%). Comparison with snow samples from 2014 to 2015 showed higher concentration of fossil elemental carbon in the more recent samples. We found an enrichment of Cu, Co, Mo, Ni and Pb and a mineral composition dominated by quartz, muscovite, albite and chloride.

Comparison of impurity concentrations from Central Asia and Switzerland indicated higher fractions of mineral dust in Central Andes. The high concentration might stem from natural erosion or from anthropogenic sources such as from close-by copper mining activities, human induced fires (agriculture, forest and heating) or fossil fuel burning from urban areas. The enrichment of certain tracer elements supports a potential anthropogenic contribution on deposited impurities, however the quantification of human induced effects is not straightforward.

Algal Growth and Weathering Crust Structure Drive Variability in Western Greenland Ice Sheet Ice Albedo

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One of the primary controls upon the melting of the Greenland Ice Sheet (GrIS) is albedo. There is a major difference in the albedo of snow-covered versus bare-ice surfaces, but observations also show that there is substantial spatio-temporal variability of up to ~0.4 in bare-ice albedo.

Variability in bare ice albedo has been attributed to a number of processes including the accumulation of Light Absorbing Impurities (LAIs) and the changing physical properties of the near-surface ice. However, the combined impact of these processes upon albedo remains poorly constrained.

Here we use field observations to show that pigmented glacier algae are ubiquitous and cause surface darkening both within and outside the south-west GrIS `dark zone', but that other factors including modification of underlying ice properties by algal bloom presence, surface topography and weathering crust development are also important in determining patterns of daily albedo variability.

We further use unmanned aerial system observations to examine the scale gap in albedo between ground versus remotely-sensed measurements made by Sentinel-2 (S-2) and MODIS.

S-2 observations provide a highly conservative estimate of algal bloom presence because algal blooms occur in patches much smaller than the ground resolution of S-2 data. Nevertheless, the bare-ice albedo distribution at the scale of 20x20 m S-2 pixels is generally unimodal and unskewed.

Conversely, bare ice surfaces have a left-skewed albedo distribution at MODIS MOD10A1 scales. Thus, when MOD10A1 observations are used as input to energy balance modelling then meltwater production can be under-estimated by 2 %.

Our study highlights that (1) the impact of weathering crust processes is of similar importance to the direct darkening role of light-absorbing impurities upon ice albedo and (2) there is a spatial scale dependency in albedo measurement which reduces detection of real changes at coarser resolutions.

Snow-Ice Spectral library (SISpec) 2.0

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The snow-ice spectral albedo is certainly one of the most important indicators to efficiently derive snow cover information from remote sensors. Spectroradiometric measurements of snow surface acquired on field, coupled with snow data such as shape and size of snow grains were organized in a spectral library (SISpec), aiming at becoming an efficient tool for image processing.

The SISpec spectral library contains snow and ice spectral signatures collected during field campaigns both in Antarctica and Arctic regions. Absolute spectral reflectance curves in the wavelength range between 350 and 2500 nm were obtained with a portable spectroradiometer, the Fieldspec FR (from Analytical Spectral Device Inc. Boulder, CO, USA), as a ratio between the radiation reflected from the measured surface and the radiation reflected by a white Spectralon panel.

Measurement sites were selected paying particular attention to the different types of snow surface characteristics (metamorphism) and taking into account the local weather conditions. In each Polar region, sites on smooth surfaces, open enough to be recognized and sampled even at the spatial resolution of satellite images (considering a 30x30 pixel area of 3x3 pixels approximately 100x100 meters) have been selected.

The nivological data relating to the surfaces examined were associated with each spectral curve, such as the shape and size of the grains, density, hardness, and snow temperature. The adopted standard for the description of the characteristics of the snow cover is the International classification for seasonal snow on the ground (2009 IASC).

The SISpec data are associated to a set of specific metadata designed to accurately describe the data in the library: spectral signature, nivological parameters (shape and size of the grains, density, hardness, and snow temperature), meteorological data.

The set of metadata has been chosen following the ISO 19115-1:2014, other shared metadata standards (es. Dublin Core) and the netCDF climate forecast (CF) metadata conventions. They comprise both administrative and descriptive metadata.

Metadata will ensure a correct organization, discovery and retrieval information and query the database.

The SISpec library will be available and searchable on-line.

Validation of Snow Extent Time Series Derived from AVHRR GAC Data at Himalaya-Hindukush

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Long-term monitoring of snow cover is crucial in climate and hydrology studies. AVHRR offers the unique opportunity to generate snow cover products on a 30- year normal climate period. To meet the increasing demand for a long-term, consistent snow product, the Remote Sensing Group in University of Bern have generated a 4-km snow cover climatology dating back to the 1980s. However, the retrieval of snow cover is not straightforward due to the artifacts introduced during data processing caused by coarse resolution GAC data and heterogeneous land cover / topography. Therefore, the accuracy and consistency of such long-term AVHRR snow data should be carefully evaluated prior to application. Here, we extensively validate snow cover retrieval from AVHRR GAC data over the Hindu Kush Himalaya due to the importance of mountainous regions for climate change studies. Additionally, the influence of snow depth, land cover type, elevation, topography, the acquisition geometry, and the sensor-to-sensor consistency have been explored using a snow climatology based on long-term station data and Landsat TM data. Preliminary results show a mean accuracy of more than 85% in comparison with Landsat data but some data set have higher deviations, which are analyzed in detail. It is inferred that this data set will become a powerful tool for assessing environmental changes in the Hindu Kush Himalaya due to the good quality and the unique length of a time series (1981 – 2019) based on almost same sensor configuration.

Assessment of a Sentinel-1 Based Soil Frost/Thaw Detection Method for Various Boreal Forest Conditions

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The continuous Sentinel-1 (S1) observations are useful in monitoring soil conditions of the top soil layer, such as the Frost/Thaw (F/T) state of the soil. Yet, in boreal forest environments, estimating the soil F/T state directly from the measured backscatter is not feasible, because the C-band signal is highly sensitive to vegetation. The backscatter contributions of the ground and the canopy can, however, be extracted using a relatively simple zeroth-order model, allowing a more accurate estimation of soil properties (Cohen et al., 2019).

Based on this modelling approach, a method aiming for near real-time monitoring of soil F/T state in boreal forest environments was developed. S1 observations together with forest property data are used to estimate the F/T state of soil in three different test areas; Sodankylä, located in northern Finland, Nurmes, in central Finland, and Tampere, in southern Finland. These sites have different forest properties considering e.g. tree height, forest density and tree species, which can influence the performance of the model used for the extraction of the ground and the canopy backscatter. The aim was to develop a method suitable for all forest types, which could be used for the monitoring of soil F/T state in all northern areas.

The backscatter contribution of the ground surface beneath the canopy and the backscatter contribution of the forest canopy, leading to the soil F/T state estimates, are retrieved in a grid with a cell size of 1 km. The input data includes S1 IW VV-pol data in 10 m spatial resolution, and forest property data (canopy cover or stem volume) originally in 16 m spatial resolution. The aggregation to 1 km grid is performed by minimizing a cost function of model estimates and observations, using all high-resolution S1 SAR image pixels within a given 1 km grid cell. Forest cover information is required to determine the forest properties for each S1 SAR image pixel, allowing to fit the forest backscatter model over a range of forest properties. In order to separate frozen and thawed conditions, the retrieved ground and canopy backscatter values are compared with corresponding reference values acquired during autumn (thaw) and winter (freeze) conditions. The soil state is finally classified as frozen, thawed or partially frozen, based on the Euclidean distances of the retrieved values from the reference values in a 2-D space. The estimated F/T state is validated against in-situ measurements of soil and air temperatures. The S1 based soil F/T estimates are also compared with the soil F/T product based on the SMOS passive microwave sensor (Rautiainen et al., 2016).

Preliminary results show generally good agreement between the S1 based soil F/T estimates and the in situ measurements in the different test areas. The S1 based estimates also correspond well with the SMOS based soil F/T estimates. The S1 based estimates are more sensitive to air temperature variations in the beginning of the freezing period, and react faster to the cooling and warming of the weather, compared to the L-band SMOS estimates. The aim for the future is to combine the S1 soil F/T estimates with existing passive microwave L-band soil F/T detection methods, which have a higher temporal resolution and soil penetration depth, but significantly weaker spatial resolution. As a result, a near real-time F/T soil state product combining the benefits of passive and active microwave sensors could be implemented.

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The Snow Climate Change Initiative: Generation of a Long Term Global Snow Climate Data Record from Multi-Sensor Satellite Data

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Seasonal snow cover is an important component of the global climate system. It is highly variable in space and time and sensitive to both short term synoptic scale processes and long term climate-induced changes of hydrologic and atmospheric systems. The accurate quantification of the seasonal snow extent and mass is an important research issue to support climate analysis and modelling. Current snow products derived from different algorithms applied to various satellite data show significant discrepancies in extent and snow mass, a potential source for biases in climate monitoring and modelling. The recently launched ESA Climate Change Initiative (CCI+) Programme addresses seasonal snow as one of 9 Essential Climate Variables to be investigated for climate monitoring and modelling applications.

In the snow_cci project, scheduled for 2018 to 2021 in its first phase, reliable fully validated processing lines are developed and implemented. Based on these tools homogeneous multi-sensors time series for main parameters of the global seasonal snow cover are generated, with focus on the snow cover area extent and snow water equivalent (snow mass). Using GCOS guidelines, the requirements for these parameters are assessed and consolidated based on output of workshops and questionnaires addressing users dealing with different climate applications as well as CCI-projects related to other essential climate variables. The procedure for snow extent product generation includes algorithms for fractional snow extent retrieval and cloud screening, generating consistent daily products for snow on the surface (viewable snow) and snow on the surface corrected for forest masking (snow on ground) with global coverage. Input are medium resolution multi-spectral data from various sensors including AVHRR-2/3, AATSR, ATSR-2, MODIS, VIIRS, and SLSTR/OLCI covering the period from 1981 to present. An iterative development cycle is elaborated and implemented to allow for homogenisation of the snow extent products from different sensors by minimizing the bias. Independent validation of the snow products is performed using high resolution snow maps derived from Landsat and Sentinel-2 data acquired across different seasons, environments and climate zones around the globe from 1985 onwards as well as in-situ snow data following the community agreed Satellite Snow Product Validation and Inter-comparison Exercise (SnowPEx) validation.

Global time series of daily snow water equivalent (SWE) products are generated from passive microwave data from SMMR, SSM/I and AMSR from 1978 onwards. The GlobSnow SWE processor serves as the baseline version. It is further improved by updating the assimilation procedure which combines in-situ snow measurements and specific satellite data. Long-term stability and quality of the product is assessed using independent snow survey data and by intercomparison with the snow information from global land process models.

The usability of the snow_cci products is monitored by close interaction with the Climate Research Group, which performs case studies related to long term trends of seasonal snow extent and snow mass, evaluation of CMIP-6 and ESM SnowMIP simulations, and modelling of hydrological regimes in periods of climate change.

In this presentation we will summarize the requirements and product specification for the snow extent and SWE products with focus on climate applications and will present an overview of the algorithms and systems for generation of the time series. Demonstration products for daily global snow extent and snow water equivalent products from different sensors will be presented and first results of the multi-sensor consistency and validation activities as well as intercomparisons with snow products from other sources will be presented.

Development Of A Homogeneous Global Climate Data Record Of Snow Cover Fraction In The Frame Of ESA CCI+ Snow

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Snow is defined as essential climate variable (ECV) by the Global Climate Observing System (GCOS). In the frame of the ESA climate change initiative extension (CCI+), snow is one of nine new parameters of ECVs to be observed by means of long-time series of satellite data. Daily global acquisitions of optical and passive microwave data available since beginning of the 1980s are used to develop homogeneous and fully validated climate data records of snow covered areas and snow water equivalent.A main objective of the snow_cci project is to generate a daily global homogenous climate data record of snow cover fraction (SCF) from medium resolution optical satellite data, meeting the requirements of users working in climate applications and modelling. The data base for the SCF climate data record includes the satellite sensors MODIS, AVHRR, AATSR/ATSR-2 and SLSTR.

In this presentation, we will focus on the algorithm development for mapping snow cover fraction and an associated uncertainty characterisation per pixel, as requested by users. In forested areas, we are preparing two thematic information of snow cover fraction, the snow viewable on the top of the forest canopy, and a canopy corrected snow cover fraction information. To assure a high quality of the climate data record, an extensive validation and intercomparison is performed as part of the development cycle, following the methods and guidelines developed in the ESA QA4EO project SnowPEx, which were accepted by the international snow community. For the validation of the SCF maps, snow reference data from high resolution optical satellite data and in-situ snow depth measurements are used. The validation results are used to improve the SCF retrieval method and to consolidate the SCF maps from different satellite sensors. We will present the status of the algorithm development for snow cover fraction, including the separation into canopy corrected an uncorrected snow in forested areas, current validation and intercomparison results, preliminary results of the global climate data record of daily snow cover fraction maps from satellite data, and an outlook of the next activities.

Towards a Global Time Series (1982- 2018) of Snow Cover Extent Based on AVHRR GAC Data

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Knowledge about the snow cover distribution is of high importance for climate studies, weather forecast, hydrological investigations, irrigation or tourism, respectively. The key aspects are the pronounced albedo change between snow cover and ground, but also water storage influencing run-off in the following spring and summer season. Distribution of snow on the globe is highly variable in space and time. Especially the annual variability of snow extent of the northern hemisphere ranges from 3 to 50 million km2 from summer to winter. Furthermore, as snow cover is very sensitive to atmospheric temperatures, it is likely to show a significant response to a changing climate. Considering the high dynamic and the vast spatial distribution only satellite data can provide the needed information. For climate studies, a time series of more than 30 years is needed for statistically sound analyses as defined by WMO. Regarding these general conditions and requirements, the only suitable sensor is the Advanced Very High Resolution Radiometer (AVHRR) on the polar orbiting satellites NOAA-6 to -19 and Metop-A to -C providing data from 1982 until today (and most likely until 2025) with daily resolution.

Based on the products of the ESA Cloud cci project, we have used the calibrated and geocoded AVHRR GAC (Global Area Coverage) data with a spatial resolution of 4 km including a consistent cloud mask. The retrieval of snow extent considers the high reflectance of snow in the visible spectra and the low reflectance values in the near infrared expressed in the Normalized Difference Snow Index (NDSI). Additional thresholds related to topography and land cover are included to derive the fractional snow cover of every pixel.

In this presentation, we show first results of the daily, global snow cover evolution spanning the complete time series of 37 years based on AVHRR GAC data and processed within the ESA CCI+ Snow project. Snow parameters, such as snow cover area percentage (SCA), snow cover duration (SCD), snow cover onset day (SCOD) and snow cover melting day (SCMD), are presented and interpreted. Furthermore, the benefits of this time series of almost 40 years fulfilling the requirements of WMO are highlighted by means of regional comparative assessments with higher resolved satellite data and in view of the climate modelling community.

Development of Long Term Hemispherical Snow Mass Satellite Data Records in the ESA Snow CCI Project

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Reliable information on snow cover across the Northern Hemisphere and Arctic and sub-Arctic regions is needed for climate monitoring, for understanding the Arctic climate system, and for the evaluation of the role of snow cover and its feedback in climate models. In addition to being of significant interest for climatological investigations, reliable information on snow cover is of high value for the purpose of hydrological forecasting and numerical weather prediction. Terrestrial snow covers up to 50 million km² of the Northern Hemisphere in winter and is characterized by high spatial and temporal variability making satellite observations the only means for providing timely and complete observations of the global snow cover. The ESA Snow CCI project strives to improve methodologies for snow cover extent (SE) and snow water equivalent (SWE) retrieval [1] using satellite data and construct long term data records of terrestrial snow cover for climate research purposes.

The efforts to improve the satellite-based SWE data record within ESA Snow CCI during the first year of the project dealt with:

• improving the retrieval methodology (the snow emission model within the SWE retrieval scheme)

• improving the consistency and stability of the synoptic weather station based snow depth data record, applied as auxiliary data source for SWE retrieval

• Utilization of optical-satellite derived Snow Extent information in SWE retrieval

• Extension of the SWE retrieval to cover the whole Northern Hemisphere, with a global gridding for output datasets

• Advanced uncertainty characterization, and improved uncertainty estimates with the SWE product

The improved retrieval methodology combines medium resolution optical data with passive microwave-based SWE retrieval to produce coarse resolution estimates (approx. 25km in the first year, and around ~10km spatial resolution during the following years) on hemispherical scale. The new retrieval approach was used to create a daily long term SWE record, spanning January 1979 to May 2018. The data record will be thoroughly assessed, characterized and analyzed in regard to retrieval accuracy and stability, changes in long term snow conditions and climatological trends in Northern Hemisphere, Eurasia and North America. The dataset will be made available for the Snow CCI climate user group in the first stage, and released for public late in 2019.

[1] Takala, M, K. Luojus, J. Pulliainen, C. Derksen, J. Lemmetyinen, J.-P. Kärnä, J. Koskinen, B. Bojkov. 2011. Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. Remote Sensing of Environment, 115, 12, 3517-3529, doi:10.1016/j.rse.2011.08.014.

Validation of ESA CCI+ Snow Products

Carlo Marin, Claudia Notarnicola, Sari Metsämäki, Valentina Premier, Kathrin Nägeli, Arnt-Børre Salberg, Gabriele Schwaizer, Rune Solberg, Andreas Wiesmann, Stefan Wunderle, Thomas Nagler
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The objective of ESA CCI+ SNOW project is the development of a sustainable robust system for monitoring parameters of the seasonal snow from Earth Observation data acquired by the European Space Agency (ESA) and third-party missions. Fully validated long-term time series of daily global snow cover extension (SCE) maps are derived from medium resolution optical data and snow water equivalent (SWE) products from passive microwave data. Snow extent products will have a spatial resolution from 1 to 4 km and will be generated for snow on the surface (viewable snow) and snow on the ground corrected for forest cover. For what concerns the SCE, the information is expressed as fractional snow per pixel (SCF). The multisensory time series, starting from the beginning of the 1980s up to now, will include data from AVHRR-2/3, ATSR-2, AATSR, MODIS, Sentinel-3A/B SLSTR and Spot/Proba-V Vegetation.

In order to validate the SCF products a validation protocol has been developed on the legacy of the ESA QA4EO snowPEx project. In detail, the protocol aims at: i) quantifying the error; ii) characterizing the performance against seasonality, forest presence, local topography, and land cover type; and iii) quantifying the error of the provided uncertainty. For this purpose, in-situ measurements and high-resolution optical data, i.e., Landsat 4-5-7-8 and Sentinel-2 data, are used. In this presentation, the detailed validation protocol and the main results obtained by assessing the first snow_cci products will be reported.

Quantifying Snow Water Equivalent by Integration of Unmanned Aerial Systems (UAS) and Ground Penetrating Radar (GPR) Surveys

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Snow water equivalent (SWE) is a key variable in hydrology and is an essential component within the Earth's climate system. However, accurately quantifying SWE at the basin scale is still a challenge. SWE is the multiplication of snow depth and snow density. Unmanned Aerial Systems (UAS) can provide very high-resolution spatially continuous snow depths at the basin scale, but are unable to measure snow densities. Ground penetrating radar (GPR) allows nondestructive snow investigation but deriving SWE profiles is often not possible from the direct analysis of radar reflections. Using UAS-derived depths and GPR two-way travel times of reflections at the snow-ground interface, snow densities can be determined. Therefore, in theory, SWE can be calculated from snow depths obtained from UAS and snow densities obtained with GPR. We investigated the possibility of quantifying SWE with such an approach. A Phantom-4 Pro UAS and a MALA GX450 HDR model GPR mounted on snowmobile were used to determine snow parameters in two surveys. A snow-free digital surface model (DSM) was obtained from the UAS survey conducted in September 2017. Then, another one in synchronization with a GPR survey was conducted in February 2019 whilst the snowpack was approximately at its maximum thickness. Spatially continuous snow depths were calculated by subtracting the snow-free DSM from the snow-covered DSM. Radar velocities in the snowpack along GPR survey lines were computed by using UAS-based snow depths and GPR reflections to obtain snow densities. The results were compared with manual snow measurements. The root mean square error (RMSE) of the obtained SWEs (370 mm average) was ±39 mm in non-vegetated regions, indicating that SWE observations with the proposed approach is good. However, the accuracy decreased in vegetation-covered areas (RMSE: ±146 mm). Using a Digital Terrain Model (DTM) rather than DSM significantly improves the accuracy in vegetation-covered regions (RMSE: ±86 mm). In order to obtain a 3D model of the snowpack, a field consisting of a grid of GPR lines spaced about 1 m was surveyed in a rectangle area of 20×10 m2. The layers within the snowpack were analyzed with the help of 3D mapping of GPR survey using a custom python package specifically developed for 3D GPR data processing and visualization.

Development Of The New Snow Water Equivalent Product H65 In EUMETSAT H SAF Project

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In the current EUMETSAT H SAF (Satellite Application Facility for Hydrology) snow product portfolio the only Snow Water Equivalent (SWE) product is H13. It is provided in the Pan European grid (from 25° W to 45° E in longitude and from 25°N to 75 °N in latitude) with resolution of 0.25 degrees (~ 25 km) as Near Real Time (NRT) service. The product is a combination of flat area product produced by Finnish Meteorological Institute (FMI) and mountain area product produced by Turkish State Meteorological Service (TSMS).

The algorithm of flat land part has since been improved in various development projects. In addition, the users have expressed interest in expanding the region. Product H65 is in development and will cover the Northern Hemisphere in EASE-Grid projection. The mountainous part is based on the current algorithm version used in H13 but will extend over Northern Hemisphere. In addition, the flat land part will have the following improvements: 1) The forward model of brightness temperatures (HUT snow model) is improved version which includes multilayer approach to snowpack 2) variable snow density is considered (different values for tundra and northern boreal forest) 3) a proper SWE error estimate is provided including systematic error component.

The authors will present the current status of the implementation of the H65 SWE product with example SWE fields and preliminary validation results.

Remote Sensing of Snow Properties with Sentinel-3 versus MODIS

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Seasonal snow is an important component of the Earth system strongly affecting the energy balance and the water cycle at high latitudes and elevations. Vast land areas sparsely populated in the north and in mountainous regions are weakly monitored by in situ sensors. Earth observation is the only practical means of frequent and accurate monitoring of snow properties in these regions. As snow properties might quickly change, moderate resolution sensors with frequent coverage (~daily) are crucial. The operational focus of the Sentinel satellites motivates their use. Sentinel-3 provides frequent coverage with moderate resolution optical sensors. The revisit time is 0.5-1.0 day over most regions having seasonal snow cover (two satellites).

This presentation gives an overview of the first experiences with the Sentinel-3 optical sensors for a portfolio of snow algorithms and products previously developed for the MODIS sensor over more than 15 years. These algorithms are now being ported, adapted and optimised for the use with Sentinel-3 OLCI and SLSTR sensors.

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, meteorology and climate monitoring. Snow cover is a key to energy balance modelling and warning of potential flood situations. Snow surface temperature and snow surface wetness give information on the progress towards and within the snowmelt season, and are important for flood warning. Snow albedo is crucial in energy balance modelling and modelling the snowmelt progress.

The presentation goes through the algorithms for the different products and compare retrieval results from MODIS and Sentinel-3. Examples of multi-sensor/multi-temporal fusion of SLSTR and Sentinel-1 SAR data will also be given. As there is no one-to-one match in general between the bands of MODIS and SLTSR/OLCI, we had to make changes and adaptations to the algorithms. There are also bias and saturation effects with some of the sensor channels. The related challenges will be discussed, and the performance between the two compared.

High Resolution Remotely Sensed Forest Datasets Facilitate High Spatio-temporal Estimates Of Snow Surface Shading For Snowmelt And Land Surface Reflectance Modelling

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Forest canopies act as intermediaries in radiation energy exchange between the atmosphere and the snow surface. Dark forests and a shaded snow surface lower the effective albedo of the land surface, causing feedbacks such as warming and increased snowmelt. Forest snow mapping from remote sensing platforms is challenged by the presence of forest canopy and the interaction between forest structures and snow surface shading under different solar and zenith angles. Algorithms can be aided with prior knowledge of shaded snow surface area, and high resolution snow cover models can help fill data gaps where remote sensing approaches fail to see snow below/between the trees.

The size, location and distribution of forest discontinuities are important controls on forest snow surface shading, but challenges arise when accounting for these vegetation characteristics at larger spatial scales. We present a high resolution solar canopy transmission model that leverages the increased availability of remotely sensed forest datasets from UAV, manned aircraft and satellite platforms. Combined with high performance computing resources for calculations at watershed scales, the model can predict incoming solar radiation at the snow surface at high spatial (meter-scale) and temporal (minute-scale) resolutions. The model calculates both direct and diffuse radiation, allowing for clear distinction between shaded and sun-lit snow surfaces. Compared with ground-based pyranometer measurements and aerial photography of shadow distributions, the model performs well using LiDAR canopy data from both UAV and manned aircraft platforms, as well as canopy height models from passive airborne and satellite sensors. Because the model incorporates fine-scale canopy discontinuities it can be used in replacement of bulk canopy descriptor parameters to improve estimates of solar radiation input to the sub-canopy snowpack, with benefits for snow cover and melt estimates at the watershed scale. It can further provide maps of snow surface shading at high spatio-temporal resolution for calculating effective surface albedo of forested areas during wintertime, which have potential applications for forest snow reflectance observations and land surface modelling.

Operational Satellite-based Daily H SAF Snow Extent Products

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In this work, we describe two currently operational H SAF snow extent products (H31 MSG/SEVIRI and H32 Metop/AVHRR) which provide daily data about snow extent.

These single sensor H SAF snow extent products aim at meteorological and hydrological applications, such as additional information for numerical weather prediction. Both product are independent of any outside data sources, such as surface observations and weather model data.

The HSAF MSG/SEVIRI snow extent product provides daily snow extent for the full MSG/SEVIRI disk. The MSG/SEVIRI product has been operational since 2008. The HSAF Metop/AVHRR snow extent product reached operational status 2018, but the product is available since 2015. It provides global daily snow extent data in 0.01x0.01 degree lat-lon grid.

The products are based on optical and IR channels which provide good spatial resolution. The geostationary MSG/SEVIRI product benefits also of the high 15 minute temporal resolution of the instrument, which improves daily coverage otherwise limited by cloud cover and darkness. Polar Metop/AVHRR product benefits of the better resolution in polar regions where geostationary satellites struggle.

We employ thresholding method based on semi-empirical approach using subjective classification of over half a million satellite pixels. The algorithms employed in these products have been developed to provide a product which prefers accuracy even if it means some pixels are not classified.

Validation results based on surface observations of snow depth and the state of the ground suggest that these products have potential for applications which need reliable single instrument information about snow cover extent.

We describe the products, show recent validation results and some examples of the products. Similar products are expected to be available when the next generation EUMETSAT weather satellites will become operational.

Comparing H SAF Snow Extent Product with MODIS and Landsat Data in Spring 2016

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The snow cover of the Northern Hemisphere is a crucial component of the global climate system. In the high latitudes, snow cover has a large influence on the hydrological cycle and, therefore, snow cover monitoring is important for hydrological and climatological applications. Due to the large area and sparse in situ measurements, snow cover monitoring at large scale is only possible from satellites. The satellite products are of interest as standalone products, but also highly valuable when used in combination with snow modelling in e.g. Numerical Weather Prediction models (NWP). The presence of snow on ground affects the near surface temperatures. It is crucial to discriminate between snow covered and snow free ground to have realistic near surface temperature forecasts. The aim of this study is to compare H SAF snow cover extent product with Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat data. H SAF data are available from 2015. The product is based on AVHRR data and provide global daily data. The algorithm of the H SAF snow extent product (H32 Metop/AVHRR) is based on multispectral threshold technique and the spatial resolution of the product is 0.01° x 0.01°. The comparison will be done for the period from March to May in 2016. The snow extent product will be intercompared with satellite data to assess coherency and to identify sources of discrepancies.

The Copernicus Global Land Monitoring Service For Snow Cover Fraction

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The Copernicus Land Monitoring Service, part of the European flagship programme on Earth Observation, provides high-quality products of different thematic fields, including cryosphere, vegetation, water and energy. As part of the cryosphere theme, we developed, implemented and are operating near real time (NRT) services for daily fractional snow cover information for the Northern Hemisphere and for the Pan-European domain from medium resolution optical satellite data with a latency time of about one day. Such services are of major interest for users working with numerical weather prediction, hydrological modelling, hydropower planning, geotechnical engineering or for national authorities responsible for natural hazard warning systems.

Two major NRT fractional snow cover services are currently supported, one for the central European domain from Terra MODIS data with about 500 m pixel spacing (CEURO_SCE500), and another for the northern hemisphere with about 1 km pixel spacing (NHEMI_SCE). The northern hemisphere snow cover fraction (SCF) service was set up based on Suomi-NPP VIIRS data and has recently been adapted to use Sentinel-3 SLSTR data in the future.

The SCF retrieval algorithm and required auxiliary data are adapted for each sensor and grid spacing. The transfer of the northern hemisphere SCF service from the Suomi-NPP VIIRS data to the Sentinel-3 SLSTR data involved several major adaptations of the cloud screening algorithm and the SCF retrieval method.

In this presentation, we will give an overview on the established NRT Snow Cover Fraction services as part of the Copernicus Land Monitoring Core Service, including information on the product quality. Furthermore, we will introduce the most recent improvements and updates of the cloud screening and snow cover fraction algorithms for using the Copernicus Sentinel-3 SLSTR data as input for the future northern hemisphere snow cover fraction service.

EUMETSAT HSAF AVHRR-Based Fractional Snow Cover Products

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EUMETSAT H SAF fractional snow cover products H12 and H35 are presented. Products H12 (SN-OBS-3) and H35 (SN-OBS-3P) are fractional snow cover (FSC) products based on AVHRR data produced in the EUMETSAT H SAF framework. The products utilize multi-channel spectrometer data of AVHRR instrument on-board MetOp satellites to determine the fractional extent of snow cover for Pan-European (H12) and Northern Hemisphere (H35) domains.

The "H12" is a daily operational product with spatial resolution of 1 to 2 km covering an extended Pan-European domain (longitudes: 25° West - 45° East and latitudes: 75° North - 25° South. The algorithm utilizes an optical transmissivity map to account for forest canopy effects and combines all the available satellite passes of given day to obtain the optimal cloud-free composite for each day (all the cloud free observations are combined for the final output product – reducing the cloud coverage for each day). H12 is produced for both for flat and mountainous regions. The algorithm for mountainous regions is slightly modified (optimized) from the one for flat lands and the final H12 product is a merged composite of the flat and mountainous intermediate products.

H35 product is essentially the extended version of H12 from pan-European region to Northern Hemisphere and uses the same approach and same algorithm as applied for the H12 product.

To improve the operational production of the H12 and H35 products, the respective processing chains have been implemented within the ecFlow workflow monitoring software during the recent year. The implementation has been turned to operational ecFlow monitoring during Q3-Q4 of 2019.