Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Home Affairs FDHA
Federal Office of Meteorology and Climatology MeteoSwiss

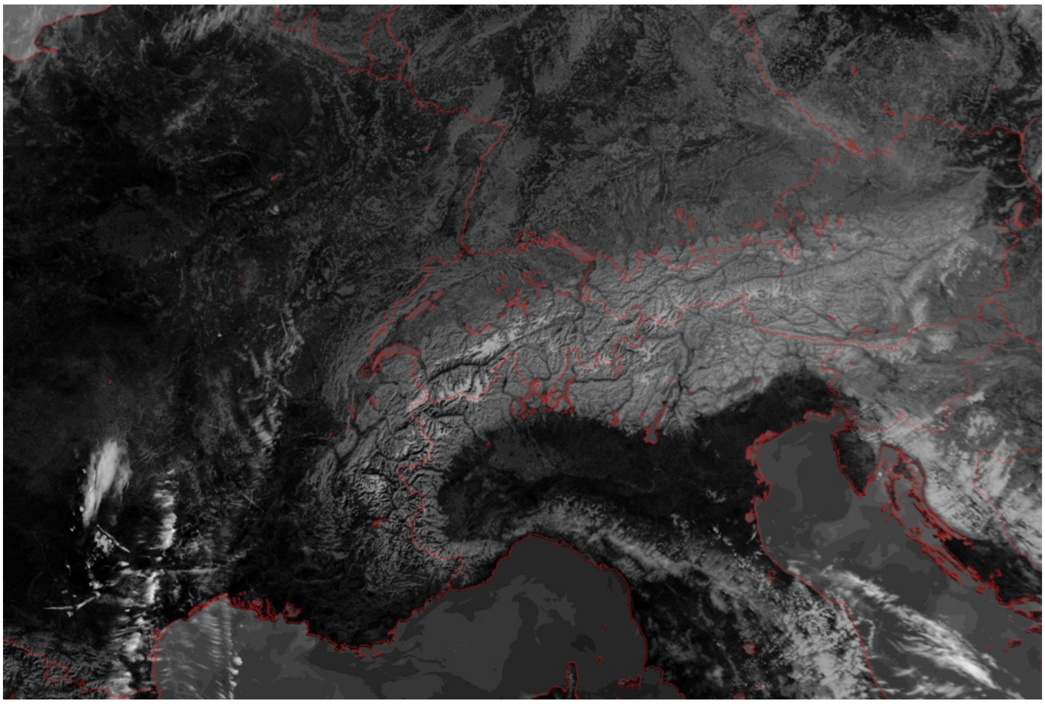
UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

GCOS Switzerland Project

Fractional snow cover time series (1981 – 2021) – a novel dataset from space to support climate studies in Switzerland

Final Report

Project Period: 01.08.2020 – 31.10.2022
Project PI: Prof. Dr. Stefan Wunderle
Project Deputy PI: Dr. Kathrin Naegeli
Collaborators: Dr. Helga Weber, Christoph Neuhaus
Institutions: University of Bern
Funding: MeteoSwiss, in the framework of GCOS Switzerland
Authors: Dr. Helga Weber, Prof. Dr. Stefan Wunderle



1 Summary

Snow is one of the most highly dynamic climate variables, which affects the evolution of the Earth's climate. Area covered by snow is a critical indicator to understand and predict the climate and is defined as an Essential Climate Variable (ECV; GCOS, 2016). Snow cover on the ground significantly impacts the climate system by 1) its high albedo, 2) heat insulation, and 3) water storage, soil moisture, and runoff contribution. Next to in-situ measurements, satellite observations play a pivotal role to obtain snow cover information and assess its changes and variability over time and space. The Advanced Very High Resolution Radiometer (AVHRR) spanning about 40 years in time, provides an unique source of temporal and spatially homogeneous information of snow cover for climate monitoring.

About 30 % of Switzerland's surface is covered by forests, but snow on ground in forests is not detected from most satellite retrievals. In this GCOS project, we developed a canopy-corrected fractional snow cover time series (1981 – 2021). The novel data set from space supports climate studies in Switzerland. The data set is based on the unique AVHRR archive, hosted at the University of Bern, with more than ~160.000 (~74.000 daytime) data sets.

The main project activities included the development of the fractional snow cover product (1981-2021), including a canopy correction approach for forested areas. The product was validated using high-resolution satellite data and an uncertainty layer calculated and added to the final snow products. The final product generation of the 1 km daily and 10-day fractional snow cover product contains quality indexes, extracted uncertainties, gap-filled pixels (caused by clouds) as well as an analysis of monthly snow maps for different elevations.

With this and for the first time, a time series of fractional snow cover (FSC) considering forested areas and including an uncertainty measure has been generated spanning over 40-year in time.

This FSC time series, respective the *AVH_FSC-v1* product, serves as a basis for climate services and can contribute to enhanced process understanding in the field of snow cover dynamics and its impact on local society. The provision of the daily and 10-day *AVH_FSC-v1* product to stakeholders such a MeteoSwiss and WSL SLF for potential integration in their databases and public accessibility is envisaged.

Credits cover image: NOAA-14, 1998-02-18 13:04, RSGB/University of Bern

2 Scientific Report

2.1 Introduction

Accurate snow cover retrieval is particularly essential in forested regions. For example, in Switzerland forest cover reaches ~30 % of the land surface. Snowmelt from forests provides therefore a large contribution to the freshwater water supply.
Forest snow processes are primarily controlled by the structure and type of the forest, with the canopies intercepting snowfall or hiding the snow on the ground. This creates large differences in snow accumulation and melt patterns. Next to solar and thermal radiation processes, wind for example plays a large role, leading to turbulent fluxes and relocation of snow. All this leads to high spatial and temporal variability of the snow cover and its reflectance on small scales.
In this project, we developed a Fractional Snow Cover Product (Level-2 and Level-3), which is corrected for canopy effects. Since optical satellite data are obscured by the forest canopy, the snow below the forest canopy is hidden if no correction is applied. Here, we applied an optimized canopy correction based on a semi-empirical reflectance model (after Metsämäki et al., 2015) to overcome the underrepresentation of snow in forested landscapes.
Choosing the historic 1 km AVHRR sensor as satellite data for the fractional snow cover product, allows to produce a time series of 40-years back in time (1981 – 2021). The time series of snow cover extent fills essential knowledge gaps on past snow occurrences over time and in a spatially homogenous way, which makes it very valuable for climate monitoring. This is of particular concern in climate-sensitive mountainous regions such as the European Alps. Using the unique AVHRR data set of the University of Bern (1981 – 2021), a high-quality 40-year time series of Fractional Snow Cover Extent (FSC) has been produced for Switzerland. It includes pixel-wise uncertainty estimates of the snow maps, conditional flags, and quality indicators for Level-2. For the Level-3 product a temporal gap-filling and aggregation procedures have been applied.
The Level-2 and Level-3 product of satellite-borne fractional snow cover extent (1981-2021) contributes to the targeted goal of the GCOS Switzerland Strategy 2017-2026. It is attributed to the strategic pillar 3, entitled with '*Ensure applicability of Swiss GCOS data and products*": Priority 3.1 and 3.2.'. The novel daily and monthly data set of fractional snow cover extent is 1) optimized for snow detection in forested regions, 2) includes pixel-wise uncertainty measures and 3) extends former space-borne time series retrievals to 40 years. The new snow product is expected to benefit climate monitoring, climate information, and climate services in applied research and to support national Swiss climate strategies. Furthermore, it will contribute to ongoing research projects, e.g., by serving as independent reference validation data set of snow depth and snow water equivalent climatologies, developed at MeteoSwiss in collaboration with SLF WSL. In addition, it provides high potential as observational reference for evaluating snow cover representation in state-of-the-art regional climate models e.g., the EURO-CORDEX initiative of MeteoSwiss and partners.

2.2 Methods and activities

The project comprised four main activities, defined in the respective work packages / tasks, to achieve the proposed objectives: 1) development of a Fractional Snow Cover Product, 2) validation and development of uncertainty information per pixel, 3) implementation of spatio-temporal gap-filling and aggregation procedures, 4) analysis of monthly time series for different elevation levels and sub-regions.
The high-level flow diagram, see Figure 1, displays an overview of the project activities. Each of these activities is described in detail in the following.

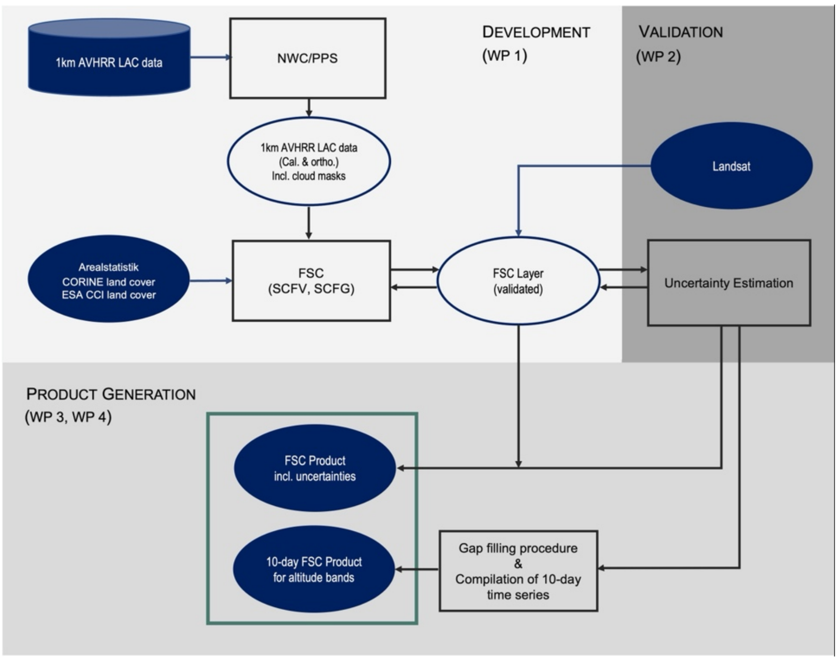


Figure 1: High-level flow diagram of proposed procedure to generate a novel FSC time series (1981 – 2021) for Switzerland. The project activities include the development of the NDSI/FSC snow product (WP1/Task1), the validation including uncertainty characterization based on high resolution satellite data (WP2/Task2) and the final product generation with the FSC product (NDSI/FSC map, cloud mask, quality index, extracted uncertainties), and the monthly FSC product of climatological monthly snow maps (WP3/Task3 und WP4/Task4). The green box indicates the final products open available for MeteoSwiss, WSL SLF and other interested organizations.

Task 1: Development of a Fractional Snow Cover Product

The 1 km AVHRR European archive hosted by the University of Bern, consists of ~160.000 (~74.000 daytime) swath satellite scenes dating from 1981 until today. For the novel Fractional Snow Cover Product, a major update in the pre-processing chain (Level-1b to Level-1c) was processed on the HPC Linux cluster of the University of Bern (UBELIX). This update implemented 1) the newest visible calibration PATMOS-X parameters (y2017r1_sbaf; after Heidinger et al., 2010; update 2017), 2) an extended thermal calibration (after Kidwell, 2000; Walton et al., 1998) to obtain robust gain values and to dampen undue high frequency fluctuations in the count data (Trishchenko et al., 2002), 3) an new software package to pre-process AVHRR/1 sensor data to improve data availability in the earlier years of the archive. In addition, a novel probabilistic cloud mask (Version: PPS v2021.1), developed by EUMETSAT NWC SAF (Nowcasting and Very Short Range Forecasting Satellite Application Facility) PPS Software Package (Polar Platform System) was implemented and processed to improve the cloud-snow discrimination.
To estimate canopy-corrected fractional snow cover, the SCAMOD algorithm after (Metsämäki et al., 2005, 2012, 2015) has been applied and adapted. In a nutshell, SCAMOD is based on a semi-empirical reflectance model, which assumes, that the observed reflectance from the target is the sum of volume scattering from the forest canopy layer and the surface from the ground. SCAMOD uses predetermined values for the static reflectance constituents (i.e., wet snow, opaque forest, and snow-free ground) and the two-way transmissivity map. As input for the two-way transmissivity map, the forest canopy transmissivity map, developed within the ESA CCI+ Snow project, has been used. To determine the reflectance constituents, a pre-study has been conducted to assess spatial varying parameterization of SCAMOD in subsets of four alpine climatological zones (Auer et al., 2007) and adapted for the AVHRR sensor characteristics (see Weber et al., 2021a). These

also included a sensitivity study analysing the impact of different forest types and its effects (Weber et al., 2021b). Testing of dynamical, pixel-based parameterization of SCAMOD instead of a static parameter retrieval using maps of CORINE Land Cover and Tree Cover Density, as well as 'Areal Statistik Daten' of Switzerland culminated in the final parameterizations of the SCAMOD algorithm: A spatial dynamical, land-cover class specific parameterization of the SCAMOD reflectance constituents based on CORINE Land Cover Map 2000.

The *AVH_FSC-v1* product calculates two fractional snow cover maps: 1) Snow cover fraction viewable from above (SCFV) without applied transmissivity, 2) Snow cover fraction ground (SCFG) with applied transmissivity to correct for snow below canopy.

For improved useability, quality indicators/flags, labeled with 'no_data', 'good', 'questionable', and 'bad', have been added as bit-encoded layers to the data comprising errors in the raw data, which have been extracted using UniBe software and NWC/PPS. In addition, conditional flags, such as a restriction of the viewing zenith angle < 40 degrees to achieve higher quality of the snow maps, classification of permanent ice and snow and forested regions were added as bit-encoded layers.

In a final step of the *AVH_FSC-v1* product development, the output NetCDF format following CF conventions have been developed. Next to the global attributes for each scene, the variables/layers (i.e., 'SCFG', 'SCFG') are labelled with descriptive attributes. An NetCDF specific encoding is applied to minimize the storage volume of the data set. See section 2.3 for further details and examples.

Task 2: Validation and development of uncertainty information per pixel

The validation strategy of the swath-based *AVH_FSC-v1* product followed the standard protocols developed within international snow projects such as the ESA CCI+ Snow and ESA SnowPEX projects. An independent validation using high resolution 30m Landsat-derived snow cover maps has been carried out by V. Premier (EURAC, Italy). The Landsat-derived snow cover maps included three different algorithms to detect snow after the Dozier (1984), Salomonson and Appel (2004), and Klein et al., (1998) approaches. The validation results are derived from a pixel-by-pixel comparison of the SCFG and SCFV layers of the *AVH_FSC-v1* product over Europe by using 127 Landsat high resolution snow cover maps (time range: 1984 to 2014). Statistical metrics for the pixel-by-pixel comparison include the Bias, RMSE, unbiased RMSE and cross-correlation. The multifold validation has been carried out for all satellite sensors, single satellite sensors, different surfaces (i.e., mountain, plain, forests, open landscape, complete viewing zenith angle range, limited viewing zenith angle (VZA) range (< 40 degree)) for each of the three validation snow maps. Table 1 displays the summary validation using the Landsat snow masks calculated with the Salomonson and Appel (1984) approach. This summary validation indicates overall better accuracy for SCFG compared to SCFV as shown by the RMSE, unbiased RSME, bias and the correlation coefficient. Considering the validation methodology, this is unexpected, but might be caused by the selection of validation scenes. However, since the goal of this study is the estimation of canopy-corrected snow cover, the SCFG, the overall results are reasonably good with a correlation coefficient of 0.811, a bias of -1.482 and unbiased RMSE of 26.207 for all land cover types and landforms. The performance of swath-based *AVH-FSC-v1* is less good for forested compared to open areas and mountain compared to plain landforms, which is expected, but the difference is very small. The validation results for satellites acquisitions with VZA < 40 degree results in a noticeable better performance. The validation results for the single satellites (i.e., MetOp-A, MetOp-B, NOAA-11, NOAA-12, NOAA-14, NOAA-15, NOAA-16, NOAA-17, NOAA-18, NOAA-19) show a wide spread of performance, e.g., for MetOp-A (NOAA-12) SCFG for forests an unbiased RMSE of 16.518 (36.64), bias of 1.918 (25.215) and correlation coefficient of 0.9 (0.585). Furthermore, validation of the bias for percentage range (0-10, 10-20, …) of the FSC shows an increasing bias from 10 to 40 % ranges, while the performance increases for FSC > ~40 % and is close to zero for FSC > ~80%. This again depends on the single satellite performance, but implies to use FSC higher then 40%, meaning that 40% of the pixel or higher is snow covered. One remaining issue is an inconsistent use of applied CORINE land cover map 2000 and the forest canopy transmissivity map, developed within the ESA CCI+ Snow project, based on ESA CCI Land cover map 2000. This impacts the *AVH-FSC-v1* product and validation procedure leading to different classification of canopy-corrected pixels due to different classifications or forested area (see Subsection 2.4 and 2.6).

Table 1: Summary validation statistics averaged for all satellites of the validation data set (i.e., MetOp-A, MetOp-B, NOAA-11, -12, -14, -15, -16-, -17, -18, -19) for SCFG (SCFV), respectively. Results are shown for different land cover types (i.e., forests, open areas), landforms (mountain, plain), all (land cover types and landforms), and limited to a viewing zenith angle (VZA) < 40 degree, which is known to increase the quality of the pixel information.

	All	**Forested**	**Open Areas**	**Mountain**	**Plain**	**VZA < 40**
RMSE	26.249 (30.602)	27.612 (33.806)	25.372 (28.448)	26.959 (24.4)	25.654 (34.856)	21.322 (30.687)
Unbiased RMSE	26.207 (26.4)	27.025 (27.033)	24.68 (25.553)	26.956 (22.665)	25.474 (28.02)	20.678 (25.268)
Bias	-1.482 (-15.477)	5.661 (-20.3)	-5.885 (-12.504)	0.426 (-9.038)	-3.04 (-20.73)	-5.201 (-17.413)
Correlation Coefficient	0.811 (0.784)	0.802 (0.759)	0.831 (0.81)	0.78 (0.827)	0.827 (0.76)	0.88 (0.803)

The pixel-wise uncertainty information includes the estimation of the total *AVH_FSC-v1* product error. The detailed methodology to evaluate quantitative uncertainty characteristics of satellite-based retrievals based on the SCAMOD algorithm is described in Salminen et al. (2018). For this project, the end-to-end uncertainty budget has been adapted following the ESA CCI+ Snow Project by A. Salberg (NR, Norway). The end-to-end uncertainty estimation for the FSC product is varying with time and location. Here, the unbiased RMSE has been estimated as pixel-wise product error determined by the systematic and statistical error. The systematic error is determined on a logistic regression model using validation images (i.e., 69 Landsat snow masks based on the Dozier approach (1984)) and model parameters based on the covariates of AVHRR channel 1, 3b, and 4 for a forest transmissivity set to 1 and FSC > 10 %. The statistical error is calculated for the transmissivity. The unbiased RMSE has been added as individual variables each for the SCFG and SCFV. For further details on the uncertainty estimation see Salberg et al., (2022). Uncertainties overall are relatively high. However, they are at similar levels in determined for the ESA CCI+ snow project.

Task 3: Implementation of spatio-temporal gap-filling and aggregation procedures

For some applications, spatial and temporal gaps mainly caused by cloud occurrence hinder consistent analysis over time and thus model implementation for e.g., hydrological applications. Therefore, a temporal snow mask gap-filling procedure has been implemented to minimize the impact of cloudy pixels. The gap-filling procedure is implemented for a daily maximum composite, calculated from one up to several overpasses a day by the different satellites based on best quality information. The temporal gap filling with a window length of +/- three days considers the neighbouring snow cover information (see Foppa and Seiz, 2012, Hüsler, et al., 2014). In this way, missing information due to clouds was filled with the pixel values of the closest clear-sky observation of the temporally neighbouring pixels forward or backward in time. Gap-filled pixel have been flagged in the quality layer, which allows users to include/exclude pixels depending on their study needs. The gap-filled daily FSC snow masks have been used to produce the 10-day *AVH_FSC10*-v1 Level-3 composites.

Task 4: Monthly time series for different elevation levels and sub-regions

The current changes observed in snow cover in the Alps and on global scale call for an improved understanding by investigations of the past. The novel FSC time series produced in this project is of unique value and allows for climate relevant investigations due to its long time-period covered. Therefore, we compiled monthly time series for different elevation bands and (sub-)regions of Switzerland. These will be the basis for an in-depth assessment of spatio-temporal snow cover dynamics in Switzerland over the past four decades (see Weber et al., 2023 in prep).

2.3 Results

The projects main results comprise 1) *AVH_FSC-v1* Level-2 and *AVH_FSC-v1* Level-3 snow product (1981-2021), 2) the *AVH_FSC-v1* derived 40-year snow climatology.
The following factsheet gives an overview and lists technical details of the *AVH_FSC-v1/ AVH_FSC10-v1* fractional snow cover product including examples of the snow maps, SCFG and SCFV, as well as their respective uncertainty maps (see Figure 2).

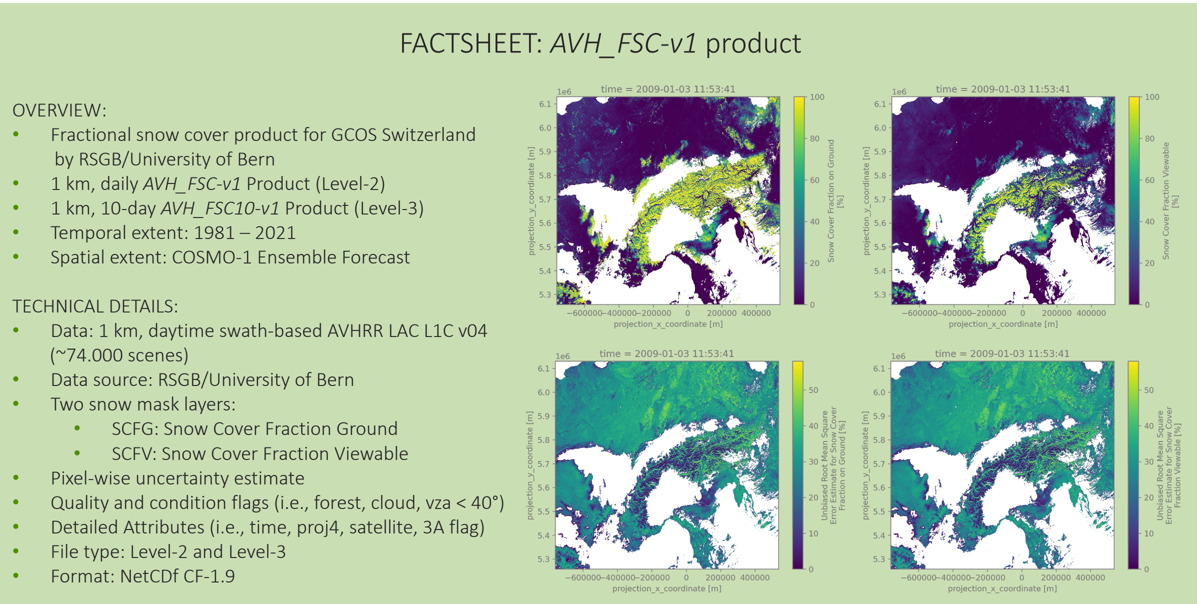


Figure 2: Factsheet of the AVH_FSC-v1 and AVH_FSC10-v1 product describing an overview and technical details of the novel fractional snow cover product. The example images of NOAA-18 (dated: 2009-01-03 11:53) show the SCFG (upper left) and SCFV (upper right) snow maps as well as their uncertainty estimations (SCFG: lower left), SCFV (lower right) for the COSMO-1E extent.

The monthly-averaged snow cover area (SCA) and anomalies of the SCFG and SCFV for the extent of Switzerland for the years 1981 until 2021 are displayed in Figure 3. Overall, SCFG has compared to SCFV a noticeable higher SCA due to the applied canopy correction as expected. The time series show high annual variability with a noticeable decrease of SCA over the last years. While the 1980s and 1990s are characterized by positive anomalies of SCFG and SCFV, the years from 2000 onwards show a tendency towards negative anomalies. The lower SCA in the years

1986 is 1990 is likely attributed to the so called ‘regime shift of snow days’ as described by Marty et al., (2008) and Schöner et al., (2018). For more details see Weber et al., (2023).

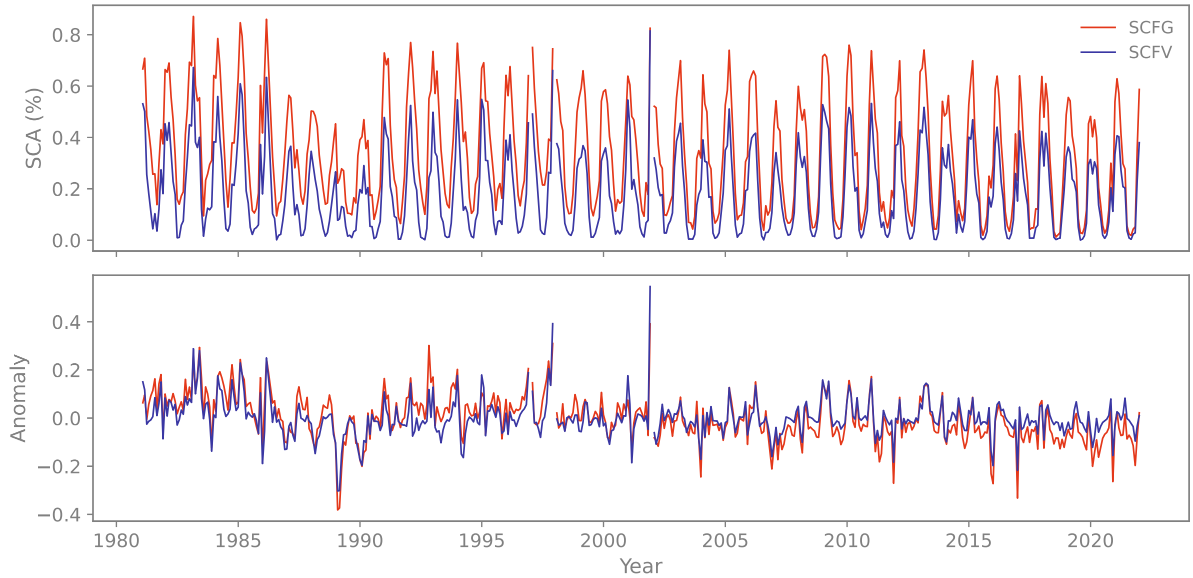


Figure 3: 40-year time series of monthly snow cover area (SCA) and anomalies of SCFG, canopy-corrected, and SCFV of the AVH_FSC-v1 product for the extent of Switzerland. Note, that no gap-filling is applied here.

2.4 Conclusions and Limitations

Snow cover is highly relevant for the Earth’s climate system as it significantly changes the surface albedo and impacts the local energy balance (e.g., heat flux between land surface and atmosphere). The high spatial and seasonal variability of snow imposes its high relevance in our changing climate.

The novel FSC products consist of daily and 10-day 1 km FSC and its uncertainty maps over the time-period from 1981 until 2021 covering entire Switzerland. The main project activities included the generation of a canopy-corrected fractional snow cover product (*AVH_FSC-v1*) from ~74.000 daytime AVHRR data (1981 – 2021), the validation, the pixel-based uncertainty characterization and the final product generation of 1 km daily and 10-day fractional snow cover product with quality indexes, extracted uncertainties, gap-filled pixels (caused by clouds) as well as an analysis of monthly FSC maps for different elevations and subregions of Switzerland.

Limitations of the *AVH_FSC-v1/AVH_FSC10-v1* product are related to the historic AVHRR L1C v04 data set even though the improvements in this project ruled out some of the previous inhomogeneities. These limitations include for example sensor degradation, orbit drift, and harmonisation. As the validation showed, certain satellite-specific characteristics are inherent in the data set (e.g., NOAA-9 and NOAA-11 orbit drift resulting in earlier overpass time which leads to twilight conditions and stronger shadowing effects in mountainous areas and thus challenges the detection of snow cover) and the performance differs between the single satellites. The probabilistic cloud mask resulted in a better discrimination of snow and clouds, but an error of up to 10% in the cloud detection is likely. The detection of ‘hidden’ snow below the canopy surface is and remains a challenge when using optical satellite images. Validation results show that a threshold of FSC > 40 % improves the product performance. Moreover, a higher quality of the product is achieved when the acquisition of the swath area is limited to a VZA < 40 degree, which avoids blurring at the scene edges. Thus, users are encouraged to apply the condition flag and limit satellites acquisitions to VZA < 40 degree. The lower SCA of the years 1986 is 1990 has been extensively investigated and are likely resulting from lower snow cover extent in this time period

(see Weber at al., 2023 for more details). A remaining issue is the inconsistent detection of forest area due to the usage of different land cover maps. This impacts the *AVH-FSC-v1* product and validation procedure leading to different classification of canopy-corrected pixels due to different classifications of forested area, but a correction is planned (see Subsection 2.2 and 2.6).
The canopy-corrected *AVH_FSC* v1 product (1981 – 2021) is a new asset for climate services and can potentially contribute to an enhanced process understanding in the field of snow cover dynamics and its impact on local society. The daily and 10-day *AVH_FSC-v1* product will be made public available and shared with stakeholders such a MeteoSwiss and WSL SLF for potential integration in their databases.

2.5 Outreach work, publication of data and results

The project development and results were shared and promoted to the research community and beyond through contributions at scientific conferences and workshops, peer-reviewed research articles, and social media channels.
Contributions at scientific conferences included the presentations of 1) an early state of the algorithm development to detect snow in forests (IGARRS, Brussels/Virtual; Weber et al., 2021b), 2) the *AVH_FSC-alpha* product version and time series at the Swiss National GAW/GCOS Symposium, Bern/Virtual (Weber et al., 2021c) 3) a statistical analysis of the seasonal snow time series and its anomalies for a subregion in the Swiss Alps (EUMETSAT Meteorological Satellite Conference, Budapest/Virtual; Weber et al., 2021d), 4) an extended *AVH_FSC*-v1-beta product at EUMETSAT Meteorological Satellite Conference, Brussels (Weber et al., 2022) and 5) an extended statistical analysis of elevation-dependent changes in snow cover patterns of the 40-years snow climatology including climate data at EARSeL Snow and Ice Workshop, Bern (Weber et al., 2023 in prep; beyond project period).
Published and planned peer-reviewed research articles include:

- Weber, H., Naegeli, K., S. Wunderle (2021). *Impact of forest canopy parameterization on space-borne snow on ground detection*. IEEE International Geoscience and Remote Sensing Symposium. IEEE. DOI:10.1109/IGARSS47720.2021.955
- Weber, H., Neuhaus, C., Premier, V., Salberg, A.-B., C. Marin, S. Wunderle (2023). *Less White: Decreasing Alpine Snow Cover derived from a 40-year AVHRR Snow Climatology*. In prep.

In the frame of this GCOS project, the Bachelors' thesis of N. Appenzeller has been successfully supervised by H. Weber and S. Wunderle. N. Appenzeller analysed two sets of AVHHR fractional snow cover maps (canopy-corrected, not corrected) and compared these data to in-situ snow measurements and weather station data in the Alpthal. The Bachelors' Thesis is entitled: 'Versteckter' Schnee in den Schweizer Alpenwäldern (2021), University of Bern.
Outreach efforts beyond the scientific community include posts on social media channels, websites, and a project presentation in the frame of the Inspiring Girls Expeditions 'Adventure of Science at Home 2021.
The *AVH_FSC-v1* and *AVH_FSC10-v1* product will be made public available and shared with stakeholders such a MeteoSwiss and WSL SLF for potential integration in their databases. Developed software (python codes) are available under request.

2.6 Outlook

The delivery is planned to Swiss stakeholders and Climate User Modeling Groups (CMUG) for an in-depth analysis of the *AVH_FSC-v1/AVH_FSC10-v1* product. This includes a presentation of the data set and offer to analysis the data set together with RSGB/University of Bern in Nov. 2022. In addition, close cooperation with the Hydrological Atlas, University of Bern, is envisaged.

A reprocessing of the *AVH_FSC-v1/AVH_FSC10-v1* product is planned to overcome the mentioned inconsistencies of the land cover maps and could also include the correction of inconsistencies as reported by CMUG.
The publication under preparation (see Subsection 2.5) will include a comparison of the FSC time series with a gridded snow depth in-situ station dataset by SLF and 500m MYD10_L2/MOD10_L2 MODIS/Aqua-Terra C6 snow product (Riggs and Hall, 2015) and presents the analysis of monthly FSC for different elevation bands and catchments of Switzerland.
As of current, the project is not planned to be continued after the above-mentioned tasks. However, this is dependent on user uptake and feedback to produce an improved *AVH_FSC-v2* product.

2.7 Acknowledgements

We highly appreciated the support of the Federal Office of Meteorology and Climatology Switzerland in the framework of GCOS Switzerland for funding this project. We also very much thank the team of the Climate Evolution Group at MeteoSwiss for their support and feedback of the novel fractional snow cover data set (*AVH_FSC-alpha*). We kindly thank Valentina Premier (EURAC, Italy) for performing the validation of the swath snow product (*AVH_FSC-v1*) using high-resolution Landsat snow masks. In addition, we thank Arnt-Børre Salberg (NR - Norwegian Computing Centre, Norway) for methodological adaptations of the uncertainty approach and calculation of the *AVH_FSC-v1* product uncertainty. We highly acknowledge the public NWCSAF/PPS Cloud Mask Software Package, released by SMHI, Sweden and valuable support by N. Håkansson and S. Hörnquist. We thank the ESA CCI+ Snow Team for providing the Canopy Correction Layer TCD LC CCI 2000. The authors acknowledge the Global Land Cover 2000 database of the European Commission, Joint Research Centre, 2003. We highly appreciate the full EEA39 PWB data of the GIO land (GMES/Copernicus initial operations land) High Resolution Layers (HRLs), which were produced with funding by the European Union (Version 2016/03/23). Big thanks goes to F. Hüsler (BAFU) for fruitful knowledge exchange. Furthermore, I want to mention the open source projects used: IPython, Xarray, Dask, Numpy, Matplotlib and Pandas.

2.8 References

Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z., and Nieplova, E. (2007). *HISTALP-historical instrumental climatological surface time series of the Greater Alpine Region*. International Journal of Climatology, 27, 17–46, doi:10.1002/joc.1377.

Dozier, J. (1984). *Snow reflectance from LANDSAT-4 Thematic Mapper*. IEEE Transactions on Geoscience and Remote Sensing, *GE-22*(3), 323-328.

Foppa, N. and Seiz, G. (2012). *Inter-annual variations of snow days over Switzerland from 2000–2010 derived from MODIS satellite data.* The Cryosphere, 6, 331–342, doi:10.5194/tc-6-331-2012.

GCOS-200. The Global Observing System for Climate. Implementation Needs. GCOS 200 (GOOS 2016). Geneva: World Meteorological Organization, 2016.

Heidinger, A. K., Straka, W. C., Molling, C. C., Sullivan, J. T., and Wu, X. (2010). *Deriving an inter-sensor consistent calibration for the AVHRR solar reflectance data record*. International Journal of Remote Sensing 31.24, 6493–6517, https://doi.org/10.1080/01431161.2010.496472

Hüsler, F., Jonas, T., Riffler, M., Musial, J. P., S. Wunderle (2014). *A satellite-based snow cover climatology (1985–2011) for the European Alps derived from AVHRR data*. The Cryosphere 8.1, pp. 73–90. ISSN: 1994-0424. DOI: 10.5194/tc-8-73-2014.

Kidwell, K.B. (1998). *NOAA Polar Orbiter Data (POD) user's guide (TIROS-N, NOAA-6, -7, -8, -9, -10, -11, -12, -13 and -14).* Retrieved October 10, 2014, from http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/podug/index.htm

Klein, A.G., Hall, D.K., & Riggs, G.A. (1998). *Improving snow cover mapping in forests through the use* of a canopy reflectance model. Hydrological Processes, 12,1723-1744.

Marty C. (2008). *Regime shift of snow days in Switzerland*. Geophysical Research Letters. Vol. Vol. 35, L12501, doi:10.1029/2008GL033998.

Metsämäki, S. J., Anttila, S. T., Markus, H. J., & Vepsalainen, J. M. (2005). *A feasible method for fractional snow cover mapping in boreal zone based on a reflectance model*. Remote Sensing of Environment, 95(1), 77–95.

Metsämäki, S.; Mattila, O.P.; Pulliainen, J.; Niemi, K.; Luojus, K.; Böttcher, K. (2012): *An optical reflectance model-based method for fractional snow cover mapping applicable to continental scale.* Remote Sensing of Environment, 123, 508–521.

Metsämäki, S., Pulliainen, J., Salminen, M., Luojus, K., Wiesmann, A., Solberg, R., Böttcher, K., Hiltunen, M., Ripper, E., (2015): *Introduction to GlobSnow snow extent products with considerations for accuracy assessment.* Remote Sens. Environ. 156, 96–108.

Trishchenko, A. P., G. Fedosejevs, L. Zhanqing, and J. Cihlar (2002): *Trends and uncertainties in thermal calibration of AVHRR radiometers onboard NOAA-9 to NOAA-16.* J. Geophys. Res., 107, 4778, doi:10.1029/2002JD002353.

Riggs, G., Hall, D., Modis Snow Products Collection 6 User Guide. https://nsidc.org/sites/nsidc.org/files/files/MODIS-snow-user-guide-C6.pdf, dated 2015-12-11.

Salberg, A.-B., K. Luojus, C. Derksen, C. Marin, R. Solberg, L. Keuris, G. Schwaizer, T. Nagler, and N. Mölg (2022). *ESA CCI+ Snow ECV: End-to-End ECV Uncertainty Budget*, version 3.0, January 2022.

Salminen, M., Poullainen, J., Metsämäki, S., Ikonen, J., Heinilä, K., K. Loujus (2018). *Determination of uncertainty characteristics for the satellite-based estimation of fractional snow cover.* Remote Sensing of Environment, 2012, 103-113. https://doi.org/10.1016/j.rse.2018.04.038

Salomonson, V. V. & Appel I., 2004. *Estimating fractional snow cover from MODIS using the normalized difference snow index.* Remote Sensing of Environment, Volume 89, Issue 3, Pages 351-360, https://doi.org/10.1016/j.rse.2003.10.016.

Schöner, W., Koch, R., Matulla, C., Marty, C., A.-M. Tilg (2018). *Spatiotemporal patterns of snow depth within the Swiss-Austrian Alps for the past half century (1961 to 2012) and linkages to climate change.* International Journal of Climatology. Vol. 39, 1589-1693, DOI: 10.1002/joc.5902

Weber, H., et al. (2021a). *Impact of forest canopy parameterization on space-borne snow on ground detection*. IEEE International Geoscience and Remote Sensing Symposium. IEEE. DOI: 10.1109/IGARSS47720.2021.955

Conference contributions

Weber, H., Naegeli, K., S. Wunderle (2021b). *Impact of forest canopy parameterization on space-borne snow on ground detection.* IGARRS. Brussels/Virtual. Talk.

Weber, H., Neuhaus, C., Naegeli, K., S. Wunderle (2021c). *Fractional Snow Cover Time Series (1981 – 2021) – a novel data set from space to support climate studies in Switzerland*. Swiss National GAW/GCOS Symposium, Bern/Virtual. Poster.

Weber, H., Augustin, H., Sudmanns, M., Neuhaus, C., Reichel, S., Tiede, D., S. Wunderle (2021d). *Leveraging of AVHH-retrieved ECV time series by using a semantic EO data cube.* EUMETSAT Meterological Satellite Conference, Budapest/Virtual. Talk.

Weber, H., Neuhaus, C., Rietze, N., S. Wunderle (2022). *Spatiotemporal analysis of Alpine snow patterns derived from a 40-year AVHRR snow climatology.* EUMETSAT Meterological Satellite Conference, Brussels. Talk.

Weber, H., Neuhaus, C., Premier, V., Salberg, A., S. Wunderle (2023). *Less White: Decreasing Alpine Snow Cover Derived from a 40-year AVHRR Snow Climatology.* EARSeL Land and Snow Ice Workshop, Bern. Talk (beyond project period).