Global Snow Monitoring for Climate Research

GlobSnow-2 Final Report

EUROPEAN SPACE AGENCY STUDY CONTRACT REPORT
ESRIN Contract 21703/08/I-EC

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ABSTRACT:

This report presents an overview on the main activities and a synthesis of key results of the ESA DUE GlobSnow-2 project. The key objective of the project was the further development of methodologies for producing long-term records of snow cover information at the global scale intended for climate research purposes. The efforts were focused on developing methodologies for the retrieval of snow extent (SE) and snow water equivalent (SWE) information based on satellite data.

The work involved acquisition of the long-term satellite data records and development of suitable algorithms and software for producing snow cover information at the global scale spanning decades. The satellite data utilized for generation of the SE product set included ESA-operated ERS-2 ATSR-2 and ENVISAT AATSR records spanning 1995-2012 and NOAA-AVHRR data for comparison studies as well as MetOp-AVHRR for NRT-products covering Europe. The satellite data applied to the generation of SWE products include measurements from two sets of sensors: SMMR and SSM/I(S) (onboard the Nimbus-7 and DMSP F8, F11, F13 and F17 satellites) that form a continuous set of passive microwave observations starting from 1979 and continuing to the present.

Conclusions on the project activities and recommendations for further work are presented in the final chapters of the report. This Final Report briefly summarizes the work, described in full, in the project deliverables listed in Table 1.1.

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ABBREVIATIONS

AATSR	Advanced Along-Track Scanning Radiometer (instrument of Envisat)
AMSR-E	Advanced Microwave Scanning Radiometer – EOS (instrument of Aqua)
ATBD	Algorithm Theoretical Basis Document
ASAR	Advanced Synthetic Aperture Radar (instrument of Envisat)
ATSR-2	Along-Track Scanning Radiometer -2 (instrument of ERS-2)
AVHRR	Advanced Very High Resolution Radiometer (instrument of NOAA-satellites)
DDF	Design Definition File
DDS	Diagnostic Data Set
DJF	Design Justification File
DUE	Data User Element
EASE-Grid	Equal-Area Scalable Earth Grid
EC	Environment Canada
ECSS	European Cooperation for Space Standardization
ECV	Essential Climate Variable
ENVISAT	Environmental Satellite of ESA
ENVEO	Environmental Earth Observation IT GmbH
ERS	European Remote Sensing Satellite of ESA
ESA	European Space Agency
FCDR	Fundamental Climate Data Record
FMI	Finnish Meteorological Institute
FSC	Fractional Snow Cover
FPS	Full Product Set
GAMMA	Gamma Remote Sensing AG
MERIS	Medium Resolution Imaging Spectrometer (instrument of Envisat)
MODIS	Moderate Resolution Imaging Spectro-radiometer (instrument of Terra)
NDSI	Normalized Difference Snow Index
NORUT	Northern Research Institute
NLR	Norwegian Linear Reflectance (algorithm)
NR	Norwegian Computing Center
NRT	Near Real Time
PS	Processing System
RADARSAT	Radar Satellite of Canadian Space Agency
RMS	Root Mean Square
RMSE	Root Mean Square Error
SCA	Snow Cover Area
SCAmod	Model for snow-covered area (algorithm)
SCDA	Simple Cloud Detection Algorithm (method for cloud screening)
SCE	Snow Cover Extent
SD	Snow Depth
SE	Snow Extent
SoW	Statement of Work
SMMR	Scanning Multichannel Microwave Radiometer (instrument of Nimbus-7)
SSM/I	Special Sensor Microwave/Imager (Instrument of DMSP-satellite series)
SWE	Snow Water Equivalent
SYKE	Finnish Environment Institute
UniBe	University of Bern
VIIRS	Visible Infrared Imaging Radiometer Suite (instrument of Suomi NPP)

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1 INTRODUCTION

The main objective of the European Space Agency (ESA) Data User Element (DUE) funded GlobSnow-2 project was the further development and implementation of methodologies for producing long-term records of snow cover information at the global scale intended primarily for climate research purposes. The efforts were focused on developing and adapting algorithms for the retrieval of snow extent (SE) and snow water equivalent (SWE) from satellite data.

GlobSnow-2 was a direct continuation of the GlobSnow-1 project, which involved acquisition of the long-term satellite data records, development and adaptation of suitable algorithms, and the implementation of software for producing snow cover information at a global scale spanning decades. A significant challenge was presented by the volume of the satellite datasets that were required for these tasks. The satellite data utilized for generation of the SE product set during GlobSnow projects included ESA operated ERS-2 ATSR-2 and ENVISAT AATSR records extending from 1995 to 2012. The satellite data utilized for the generation of SWE product included measurements from two sets of sensors: SMMR and SSM/I(S) (onboard the Nimbus-7 and DMSP F8, F11, F13 and F17 satellites) that form a continuous set of passive microwave observations starting in 1978 and continuing to the present.

The production of the long-term SE and SWE product sets included i) development and adaptation of suitable algorithms for production of multi-year datasets; ii) evaluation and validation of the algorithms by utilizing independent reference data from across the Northern Hemisphere; iii) development of software capable of processing the vast amounts of satellite data within the project timeframe; iv) carrying out the production of the SE and SWE time series; and v) archiving and disseminating the final SE and SWE product sets for the user community.

The GlobSnow SE product is the first northern hemisphere, daily, moderate resolution record of fractional snow cover (% snow cover within each grid cell) that has been produced from ESA ATSR-2 and AATSR measurements. The GlobSnow SE dataset complements previous records with longer temporal coverage but a lower spatial resolution (AVHRR 1980-2011; Zhao and Fernandes, 2009) and records with similar resolution but a shorter time series (MODIS 2001-2011; Hall et al., 2002) and is a unique dataset enhancing our understanding of historical snow conditions.

The GlobSnow SWE product is the first satellite-based daily SWE dataset for the non-alpine northern hemisphere that extends over 30 years. The previous existing daily SWE records have spanned a shorter time period (2002-2011; Kelly, 2009), had a regional focus (Derksen et al, 2003) or described the snow conditions on a monthly basis (1978-2011; Armstrong and Brodzik, 2002). The GlobSnow SWE record utilizes a novel data-assimilation based approach for SWE estimation which was shown to be superior to the previous approaches depending solely on satellite-based data (Takala et al. 2011, GlobSnow-2 Deliverable DEL-21a).

Complementary to the long-term SE and SWE time series, an operational near-real time (NRT) snow information service was implemented which produces daily northern hemisphere maps of SE and SWE based on the same methodologies applied to historical satellite measurements within the project. As a back-up service, MetOp-AVHRR was considered for Europe with an adapted processing chain to generate daily SE maps. The efforts of the GlobSnow project are thoroughly documented in the project reports, listed in Table 1.1. The GlobSnow product set, all the documentation and a sub-set of the independent validation data are available at the GlobSnow web site (http://www.globsnow.info).

The GlobSnow-2 project was a direct continuation to GlobSnow-1 project with additional partners: (Remote Sensing Group, University of Bern (UniBe), Federal Office of Meteorology and Climatology (MeteoSwiss) and Central Institute for Meteorology and Geodynamics (ZAMG) initiated in November 2008, and was coordinated by the Finnish Meteorological Institute (FMI). The project partners were NR (Norwegian Computing Centre), ENVEO IT GmbH (ENVEO), Finnish Environment Institute (SYKE), GAMMA Remote Sensing AG (GAMMA), Environment Canada (EC) and Northern Research Institute (Norut).

The GlobSnow-2 project has succeeded in enhancing the state of the art in the generation of long-term data records on snow cover, based on remote-sensing measurements, through the refinement and improvement of the algorithms implemented in GlobSnow-1, more extensive validation of the SE and SWE data records, and broad-based applications development with the GlobSnow user community.

Table 1.1: Project reports prepared during the ESA GlobSnow-2 project.

Deliverable No	***Title***
DEL-4	Summary of User Consultation Meeting-1
DEL-6	Algorithm Theoretical Basis Document (ATBD) for SWE Algorithm
DEL-8	SWE Preliminary Validation Report
DEL-9	Algorithm Theoretical Basis Document (ATBD) for SE Algorithm
DEL-11	SE Preliminary Validation Report
DEL-12	SE and SWE Operational Processor Qualification Review Report
DEL-13	Product User Guide (for both SE & SWE products)
DEL-14	Review of Progress Towards Sustainability
DEL-19	Summary of User Consultation Meeting-2
DEL-20	White paper on user requirements for satellite derived snow information
DEL-21a	Full Validation and Intercomparison Report for SWE product
DEL-21b	Full Validation and Intercomparison Report for SE product
DEL-22	Technical Note on the potential exploitation of Sentinel data for snow monitoring
DEL-23	Technical Note on the potential to produce a Snow Cover ECV, consistent with other satellite based global land ECVs
DEL-25	Final Report (this document)

2 OVERVIEW OF PROJECT WORK AND RESULTS

2.1 Snow Extent

The GlobSnow SE product portfolio includes maps of Fractional Snow Cover (FSC, range 0–100% or 0–1) on a 0.01°×0.01° geographical grid which covers the Northern Hemisphere between latitudes 25°N–84°N and longitudes 168°W–192°E. GlobSnow SE products are based on data provided by ERS-2/ATSR-2 (1995–2003) and Envisat/AATSR (2002–2012), so that a continuous dataset spanning 17 years is obtained. Three different versions of the dataset are available: v1.2 as an outcome of GlobSnow-1 (2008-2011) and versions 2.0 and 2.1 as an outcome of GlobSnow-2.

Additionally, AVHRR data were used for inter-comparison studies (European Alps) and as backup for NRT-processing for Europe. The considered AVHRR_SPARC dataset consists of daily 1-km gridded binary snow cover maps for the European Alps generated from a full-resolution AVHRR data archive (Hüsler et al. 2011). The SPARC AVHRR product is provided in a geographical (latitude/longitude) coordinate system with a resolution of 0.01°x0.01°. The product covers the European Alps from 40°N to 50°N and 0°W to 17°E. For inter-comparison with the GlobSnow-2 SE v2.1 product data set consisting of the years 1999, 2003, 2004, 2006 and 2010 were selected.

Starting from 2013, GlobSnow SE production has been relying on data provided by Suomi NPP VIIRS, with hemispheric daily coverage. The methodology for SE production is adjustable to various optical and near-infrared sensors; therefore transition from (A)ATSR to VIIRS was straight forward particularly due to partly similar spectral bands of these sensors.

2.1.1 Product development

The Fractional Snow Cover as provided by the GlobSnow SE product is based on the *SCAmod* method described in Metsämäki et al., (2005), originally developed for Northern Europe boreal forest and sub-arctic regions for the needs of SYKE's hydrological forecasting. The semi-empirical reflectance model-based method *SCAmod* originates from the radiative transfer theory and describes the scene reflectance as a mixture of three major constituents – opaque forest canopy, snow and snow-free ground, which are interconnected through the *apparent forest transmissivity* and the snow fraction. In the beginning of GlobSnow-1 project, SCAmod was chosen to be applied to non-alpine regions while the linear spectral unmixing method *NLR* (Solberg and Andersen, 1994; Solberg et al., 2006) was to be applied to mountain areas (the borderline as indicated by a mountain mask).

Thus, the very early task in GlobSnow-1 was to modify the methods to expand the application area to cover the whole GlobSnow geographical domain. For NLR, the calibration approach was revised, in particular for covering a wide range of latitudes with varying solar zenith angle. For SCAmod, this required i) the establishment of a NH forest transmissivity map, an essential input to the FSC retrieval and ii) the determination of generally applicable values for the reflectance constituents. Ideally, the transmissivity can be generated using reflectance data acquired under full snow cover conditions (Metsämäki et al., 2012). At a hemispheric scale, this approach would be very laborious to accomplish; therefore, a method for generating the transmissivity indirectly through a statistical analysis between land cover data (ESA GlobCover) and regional transmissivity maps was developed for GlobSnow purposes (Metsämäki et al., 2012). Transmissivity was first determined from MODIS reflectance acquisitions for several extensive 'training areas' in the Northern Hemisphere. From the training areas, transmissivity statistics (mean and standard deviation) were determined for all the relevant land cover classes (as provided by ESA GlobCover data). These statistics and GlobCover map were then applied to generate transmissivity estimates to the entire GlobSnow geographical domain. For the reflectance constituents, static values were derived from representative MODIS reflectance observations as well as at-ground spectroscopy.

The development of a simple, computationally low-cost cloud screening method was also one aim of the project. For this purpose, a cloud masking algorithm *SCDA* dedicated to (A)ATSR-based snow mapping (Metsämäki et al., 2011) was developed. This method uses a set of empirically derived thresholding rules based on (A)ATSR spectral bands and their ratios.

During the development work, algorithms and products were evaluated using Europe as a study area. A comparison of SE prototype products with other Earth observation snow products, in situ snow observations, and high-resolution data was carried out. These evaluations were used in the verification of the product quality. Finally, applying the developed methods and parameterizations within the GlobSnow-1 project, the production and release of SE v1.2 data record took place in 2011.

At the early stage of GlobSnow-2 project, method development was still related to the combined use of both *SCAmod* and *NLR*. Efforts for improving their performance included the determination of post-winter snow-free ground reflectance statistics. Eventually, however, using two different methods produced inconsistencies at the borders of the alpine mask, which were visually evident in v1.2 SE products. To address this artefact of applying two distinct algorithms, it was decided that only one method would be applied hemispherically. The *SCAmod* method was found to provide similar accuracy as *NLR* for mountains and non-forested plains, while providing a superior performance for forests, so it was chosen to be applied for the entire geographical domain of GlobSnow. In addition, the earlier static value for the snow-free reflectance was replaced with a spatially varying field, based on MODIS reflectance time-series analysis combined with GlobCover data (Salminen et al. 2013; GlobSnow-2 SE ATBD).

An objective of GlobSnow-2 was to improve the FSC retrievals in dense forest areas, due to evident FSC underestimations, for instance in Siberia. It was recognized that the NH transmissivity map was not representative for the densest forests, so the necessary task for improving it was assigned to SYKE. Originating from the applied method for transmissivity generation, the problem was traced back to certain GlobCover classes which were very heterogeneous in terms of forest density and thus the transmissivity. Taking advantage of the fact that very low albedos from wintertime (undercanopy) snow-covered dense forests are observed, these GlobCover class-specific transmissivities were adjusted according to the visible white-sky albedo as provided by ESA GlobAlbedo data (Metsämäki et al., 2015; GlobSnow-2 SE ATBD). The resulting new transmissivity map was a major achievement in GlobSnow-2 and led to significantly improved capability of the SE product to capture snow in dense forest areas.

At the end of phase-1 a first validation effort was undertaken to proof the above mentioned developments. DEL-11 contains an extensive compilation of validation work of the AATSR SE and AVHRR SE products based on different reference data and for several areas/countries with different land cover, topography, and climate, respectively. Landsat-TM/ETM+ data, snow depth measurements as point information and their spatial distribution (snow course measurements) as well as modelled snow depth data were used as reference data. Overall, a high agreement between the GlobSnow SE products (fractional and extent) and the different reference data sets has been found. While it is very high over flat areas it slightly decreases in complex topography (European Alps), especially in the mid-altitude levels and for *SCAmod* AVHRR. However, it is assumed that the reference data are not representative for an area of a km^2 covered by AATSR and AVHRR in such terrain. There is a slight tendency to overestimation of snow events by *SCAmod*, indicated by a high false alarm rate and a small number of missed observations at these specific sites.

Finally, it could be shown that there is no obvious bias between *AVHRRscamod* and *AATSRscamod* (for clear-sky cases) but differences depending on land cover/land use. These findings might indicate that a combination of AVHRR with AATSR snow extent products might be feasible to extend the time series of AATSR to fulfil the requirement for a fundamental climate data record (FCDR).

The GlobSnow-2 SE method development also concerned the improvement of the *SCDA* cloud detection algorithm, particularly focusing on discrimination between clouds and patchy snow cover, however not at the expense of false cloud omissions during the snow season. This work led to *SCDA2.0* which is based on the earlier *SCDA* but introduces several extra rules and adjustments for the applied thresholds (Metsämäki et al., 2015; GlobSnow-2 SE ATBD).

At the end of 2013, ESA released a new version #3 for (A)ATSR level 1b data. These data were utilized as input to the GlobSnow SE processing line. Employing the above described improvements in SCAmod parametrizations, v2.0 SE data record was processed and released in December 2013. As a new feature, this data record also included an uncertainty layer (see section 2.1.4.3). It was found later that v2.0 SE products whenever based on AATSR suffer from inconsistencies in the geolocation, due to the update in level 1b georeferencing not accounted for by the GlobSnow SE-processor. This problem was fixed and a new v2.1 SE dataset was produced for the AATSR era.

2.1.2 Product description

The *Daily Fractional Snow Cover* (DFSC) product provides fractional snow cover in percentage (%) per grid cell for all satellite overpasses of a given day. If there are multiple snow observations within a single day (only for northern regions), the satellite observations applied are those acquired under the highest solar elevation. The FSC is provided only for observations at sun zenith angle < 73°. The *Weekly Aggregated Fractional Snow Cover* (WFSC) product provides per-pixel FSC from the last available cloud-free observation within the past seven days. The *Monthly Aggregated Fractional Snow Cover* (MFSC) product is based on DFSC products for the given calendar month. Fractional Snow Cover is provided as an average of all available cloud-free estimates within the period. The *Daily 4-classes Snow Cover* (D4FSC) product provides snow cover classified into four categories per grid cell for all satellite overpasses of a given day. In terms of FSC, the four classes represent:

- $0\ \% \leq FSC \leq 10\ \%$
- $10\ \% < FSC \leq 50\ \%$
- $50\ \% < FSC \leq 90\ \%$
- $90\ \% < FSC \leq 100\ \%$

Weekly and monthly products based on D4FSC are also provided, with the same specifications as the daily products. The dataset is available at www.globsnow.info/se/. Figure 2.1.1 presents an example of daily, weekly and monthly SE products for April 2006.

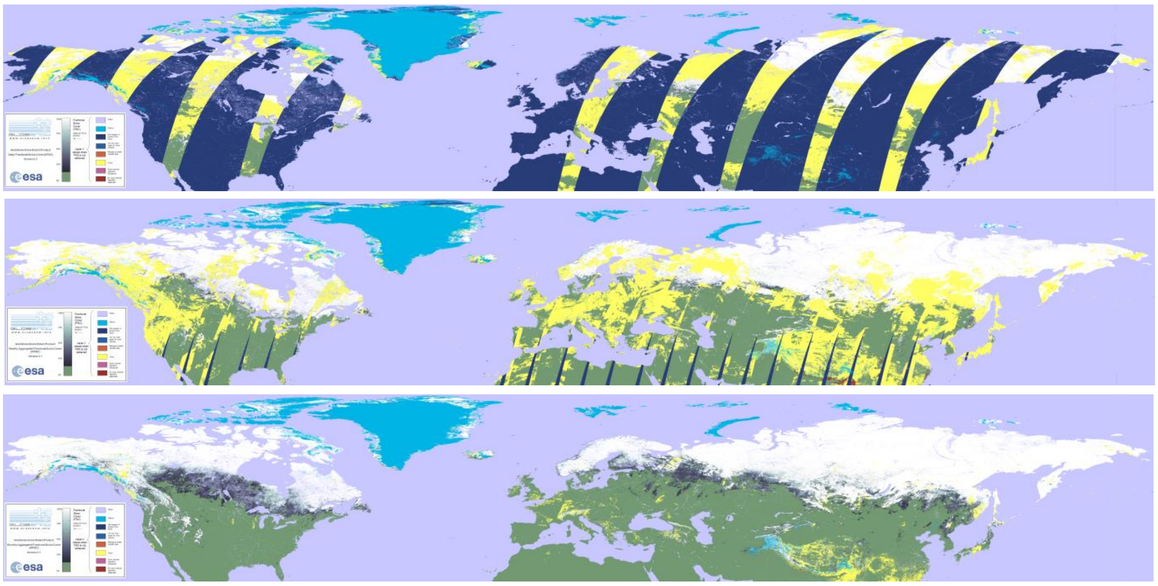


Figure 2.1.1. A sample set of GlobSnow v2.1 SE products for April 2006. *Top*: daily product for 13 April, *Middle*: weekly product for 15 April, *Bottom*: monthly product.

The product time series is updated in near real time and can be freely downloaded via web or FTP at www.globsnow.info/se/.

Each product type includes a set of layers. For all SE products the first layer contains thematic information on the snow extent. For visualization, a common colour legend was defined, as shown Figure 2.1.2. The additional layers depend on the product type.

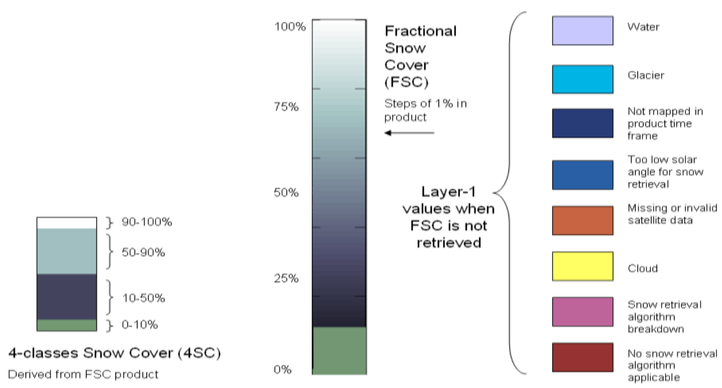


Figure 2.1.2: Colour legend for thematic layer of the SE products

The products are delivered in NetCDF format. Quick-look images are provided for quick and easy browsing in Portable Network Graphics (PNG) format. The products are stored at the Finnish Meteorological Institute and made freely available through both web and FTP interfaces.

For the comparison study University of Bern processed AVHRR data as a binary SE-product (*AVHRR_SPARC*) and as fractional SE-product (*AVHRR_SCAmod*) applying the GlobSnow retrieval algorithm. The NRT-backup system produces daily fractional snow cover (AVHRR) for Europe based on the data of MetOp-1 morning overpass. The classification and color legend is identical as described for AATSR data, and example product is presented in Figure 2.1.3.

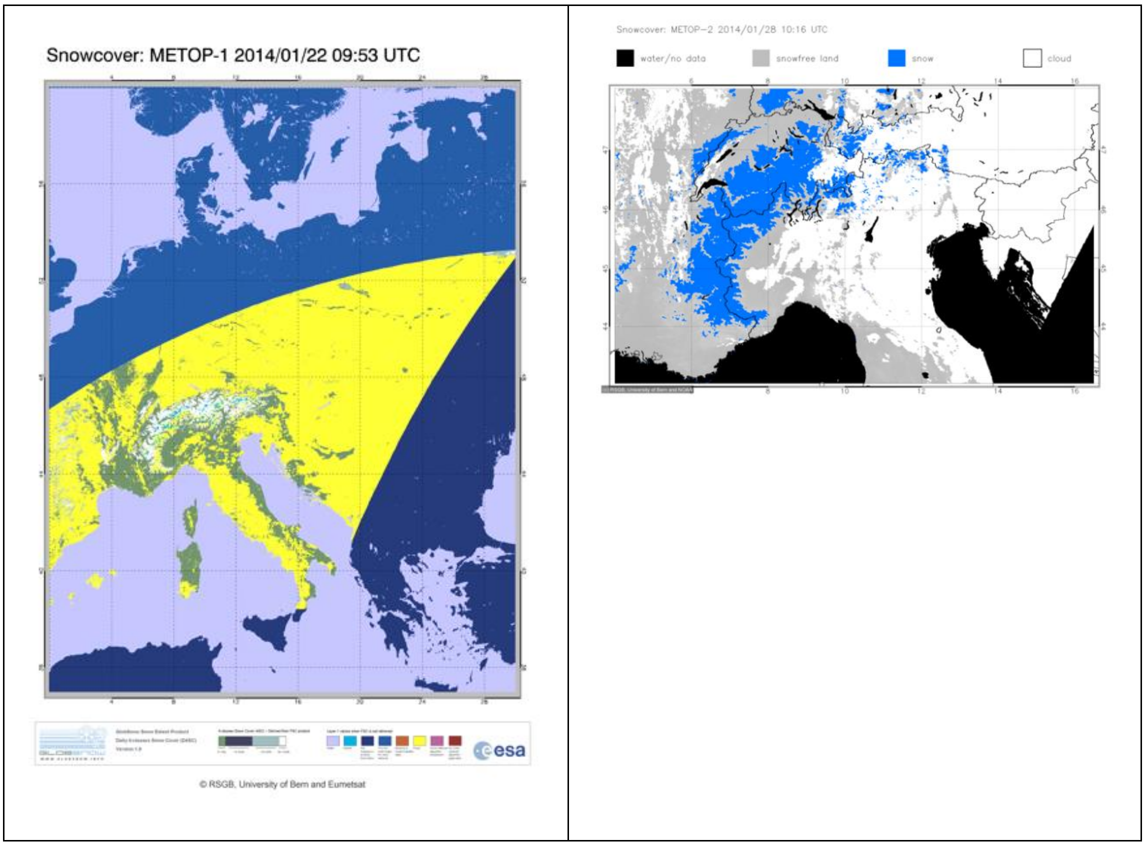


Figure 2.1.3: Example of daily snow cover based on AVHRR data for January 2014. Left: NRT-backup fractional snow cover. Right: Binary snow cover product for the European Alps.

Starting from 2013, GlobSnow NRT SE production has been relying on data provided by Suomi NPP VIIRS, with hemispheric daily coverage. Examples of daily, weekly and monthly SE products from Suomi NPP VIIRS are shown in Figure 2.1.4.

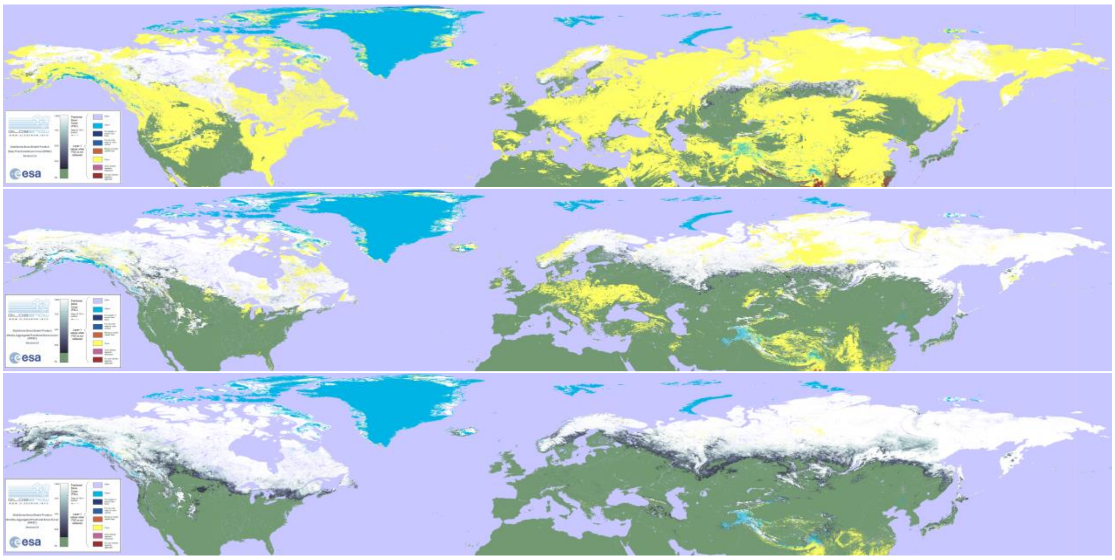


Figure 2.1.4. Example of daily weekly and monthly SE-products based on Suomi NPP VIIRS for April 2014. *Top:* daily product April 15, *Middle:* weekly product April 15, *Bottom:* monthly product.

2.1.3 Processing system

The GlobSnow processing system reads ESA provided Level 1B data and transfers them to the GlobSnow SE latitude-longitude grid based on the geolocation grid tie points provided within the data using bi-linear resampling. All orbits within the product geographical domain available within a day are processed and combined into orthorectified one day mosaics. The local solar illumination geometry and a digital elevation model (DEM) are applied to compute a terrain illumination model which is applied for radiometric topography correction. After cloud screening, the FSC retrieval method *SCAmod* is applied to the terrain and illumination corrected reflectances for the pixels interpreted as cloud-free. Statistical uncertainty for all cloud-free pixels is also determined. Finally, some thematic masks (e.g. permanent snow and ice/glacier, water, missing/invalid data) are used for final product generation. These procedures are described in more detail in GlobSnow-2 SE ATBD.
The processing software, running on a Linux OS-based Bright Beowulf cluster has been written in ANSI C and is operated at the FMI Sodankylä satellite data center, which also houses the data for the user community (at www.globsnow.info).

2.1.4 Algorithm

2.1.4.1 SCAmod method

The semi-empirical reflectance model-based method *SCAmod* originates from the radiative transfer theory and describes the scene reflectance as a mixture of three major constituents – opaque forest canopy, snow, and snow-free ground, which are interconnected through the *apparent forest transmissivity* and the snow fraction. Transmissivity, in turn, can be derived from the *SCAmod* reflectance model employing reflectance observations under conditions that highlight the presence of forest canopy – namely in the presence of full snow cover on the ground. Assuming the transmissivity can be determined with an appropriate accuracy, *SCAmod* enables the consideration of the masking effect of forest canopy on fractional snow cover estimation (Metsämäki et al., 2005, 2012; GlobSnow-2 SE ATBD).

In GlobSnow, *SCAmod* employs top-of-atmosphere reflectance acquisitions of ATSR-2/AATSR Band 1 (545–565nm) as input. The feasible values for the three reflectance constituents are based on MODIS band 4 (550nm) reflectance observations and field spectroscopy. Transmissivity is derived from SCAmod reflectance model using reflectance acquisitions from fully snow-covered terrain, which allows the unknown FSC to be neglected and reduces the equation to a linear interpolation problem.

Since the *SCAmod* reflectance model method relies on a single band and is therefore sensitive to the representativeness of the *SCAmod* parameterization as well as atmospheric effects on the observed reflectances, additional rules for detecting snow-free ground conditions were established in GlobSnow-2. These include the employment of Normalized Difference Snow Index (NDSI) and surface brightness temperature in determination of thresholds for assigning a pixel as 'snow-free'.

SCAmod may result in FSC>1 (100%) if the observed reflectance is higher than the maximum allowed by the model with the applied parameters. This may be due to the non-representative transmissivity or, more likely, to a prevailing snow reflectance higher than that applied in the model. Likewise, *SCAmod* may result in FSC<0 if the observed reflectance is lower than the minimum allowed by the model. Consequently, fractional snow cover is constrained to upper and lower limits of 100% and 0% respectively.

2.1.4.2 SCAmod parameterization

SCAmod uses predetermined values for the three reflectance constituents and for the transmissivity. The success of FSC retrievals therefore depends on the representativeness of these model parameters. It should be noted that the parameters have been determined mostly using Terra/MODIS acquisitions. This is because the narrow swath width of the ATSR-2/AATSR drastically reduces the amount of suitable observations while MODIS provides daily global coverage. The ATSR-2/AATSR spectral bands used in GlobSnow SE product generation correspond well to MODIS, so this is considered a reasonable approach. In GlobSnow-2, a particular focus was on the development and adjustment of two parameters: the apparent forest transmissivity and the snow-free ground reflectance. As a result, spatially varying (temporally static) fields for these variables were obtained.

Transmissivity was first determined from MODIS reflectance acquisitions for several extensive 'training areas' in the Northern Hemisphere. For each area, transmissivity statistics (mean and standard deviation) were determined for each GlobCover class; these were then combined to obtain class-stratified values. The transmissivity for each 0.01º pixel can be expressed as a linear combination of class-wise average transmissivity and the occurrence of the corresponding classes in that pixel (4×4 GlobCover 0.0025º pixels in one GlobSnow pixel). The feasibility of this approach was verified by evaluating the FSC retrievals against Landsat TM/ETM+ -based FSC and against Finnish *in situ* FSC measurements. These evaluations are presented in detail in Metsämäki et al., (2012).
The GlobCover-based approach would benefit from external data accounting for the forest density. To still improve the transmissivity map, visible white-sky albedo as provided by ESA GlobAlbedo (Müller et al., 2012) was selected for the discrimination of dense forest and very dense forests in certain GlobCover classes representing a wide range of forest densities. The

analysis between the albedo from selected wintertime 8-day composites during complete snow cover showed that there is a high linear correlation between the albedo and MODIS-derived transmissivity particularly around very low values. Using this linear relationship, transmissivity values for the densest forest were adjusted to be lower than in the original transmissivity map (GlobSnow-2 SE ATBD). The resulting two-way transmissivity map for the Northern Hemisphere is presented in Figure 2.1.5.

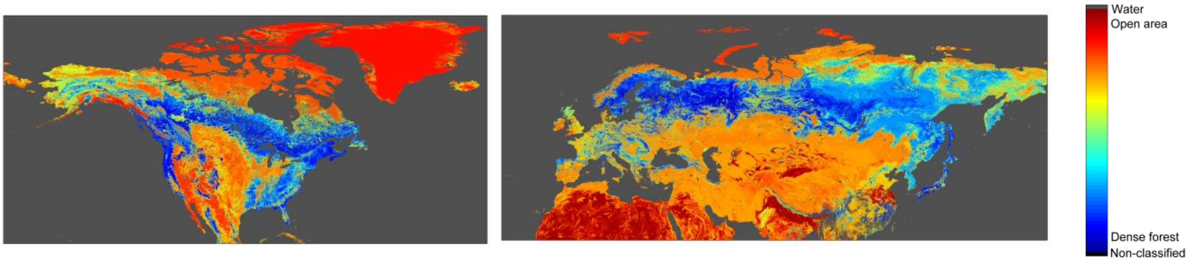


Figure 2.1.5. Map of the apparent two-way forest transmissivity map (t^2) for North America (*Left*) and for Eurasia (*Right*).

The further development of the algorithm also included the advanced consideration of snow-free ground reflectance. The reflectance of snow-free ground was improved to consider values specific to different land cover types, instead of using a single constant value for all terrain types. This was accomplished by detecting snow-free ground reflectance for different land cover classes from MODIS TOA reflectance data time series during the spring-time period. The analysis was carried out for test regions in Europe and North America. Additionally, for the regions of bare (non-vegetated) ground an analysis of MOD09 reflectance products was carried out in order to extract values for surface reflectance at snow free conditions. As an outcome, a catalogue of snow free ground reflectance mean values and standard deviations were obtained for different GlobCover land cover categories, and they are utilized in the version 2.1. SE product processing (GlobSnow-2 SE ATBD for details). The methodology and work for the European test areas is described in Salminen et al. (2013). The final snow-free ground reflectance map is presented in Figure 2.1.6.

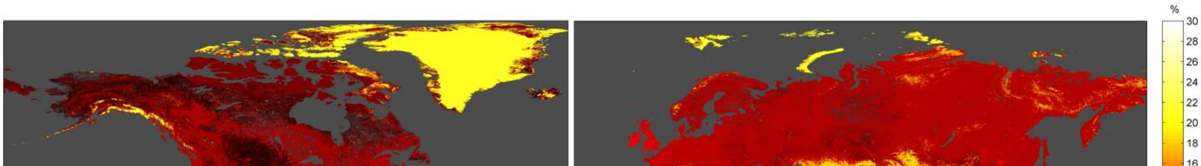


Figure 2.1.6. Snow-free ground reflectance maps applied in the GlobSnow v2.0 and v2.1 SE production: North America (*Left*) and Eurasia (*Right*).

2.1.4.3 FSC uncertainty

An additional significant improvement during the second phase of the project was the consideration of statistical uncertainty for FSC estimates and the provision of these estimates as a separate layer of the SE product. The uncertainty represents an estimate of the (unbiased) error standard deviation of each FSC value of the product. This standard deviation is obtained through an error propagation analysis that considers the statistical accuracy of each reflectance or forest transmissivity contributor in the SCAmod algorithm (see Metsämäki et al. (2005) and GlobSnow-2 SE ATBD for details). For example, the estimated standard deviation of snow free ground reflectance of each land cover class is taken into account when the uncertainty characteristics are determined for the pixel under investigation and for a given time. Thus, the uncertainty is provided for each individual FSC estimate and varies in space and time, depending on the level of FSC. Figure 2.1.7 presents an example of the uncertainty for the monthly product, April 2006.

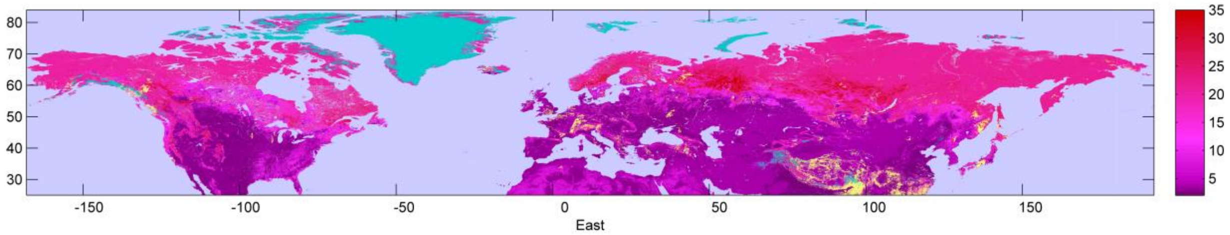


Figure 2.1.7. Uncertainty layer for v2.1 SE Monthly product, April 2006. Statistical error (non-biased standard error) for each FSC estimate is provided in FSC %-units. A yellow color indicates cloudy areas, cyan indicates non-classified areas of permanent snow and ice (see class 'Glacier' in Fig. 1), according to the GlobCover data.

2.1.5 Product evaluation and intercomparison

For the evaluation and intercomparison of the daily GlobSnow-2 SE v2.1 products (DFSC) reference data with different spatial extent and pixel size were selected, including hemispheric and continental snow products from MODIS data provided by NSIDC (MOD10_L2) and CryoLand (Pan-European FSC), respectively, regional binary and fractional snow maps from AVHRR, Landsat 5 TM / 7 ETM+ and Kompsat-2 data and local snow information from in-situ measurements. The years 2003, 2004 and 2010 were selected as main periods for intercomparison. Depending on the availability of reference data additional years or the full period from 1995 - 2011 were used for intercomparison and evaluation activities.

Intercomparisons were performed whenever valid pixel information was available in both, the DFSC product and the selected reference snow product. Invalid pixel information such as cloud cover, water bodies or no-data values were excluded. For assessing the product performance in different environments (additionally to the total area covered by the DFSC and the selected reference products) different surface classes including forested, non-forested, plain, mountain, plain forested, plain non-forested, mountain forested and mountain non-forested areas were discriminated.

Binary and fractional snow cover products from other sources were resampled (if needed) to the pixel size of the DFSC, and then intercompared pixel by pixel with the DFSC products, analyzing the matching of the products by statistical measures, and, for snow products with hemispheric and continental extents, the generation of difference maps. For intercomparison with the AVHRR snow maps and with in-situ snow observations the DFSC products were converted into binary snow maps using the two thresholds 15 % and 50 %. For generating binary snow information from in-situ snow depth measurements the thresholds of 1 cm and 15 cm were applied. Snow maps from high resolution satellite data were generated by different approaches, including the snow mapping algorithms from Salomonson and Appel (2006), Klein et al. (1998), Dozier and Painter (2004) and ENVEO (Nagler et al., 2012). The snow map generation from very high resolution optical satellite data was based on a Mahalanobis distance classification (Mahalanobis 1936; Richards, 1999) or K-means clustering (MacQueen, 1967) followed by manual mapping.

The intercomparisons of the selected snow products with the DFSC show mean annual RMSD in the order of 10 %, with mean Bias between -3.5 and 3.5, and mean standard deviations in the order of 25 %. Intercomparisons of DFSC with snow products from individual scenes result in RMSD ranging between 1 % and 30 %, but deviations for particular surface classes are partly even larger, up to 38 % for mountain forested areas. In general, major differences were found for forested areas in plain and mountainous terrain, while the detection of fractional snow in plain non-forested areas by different snow products matches well in most cases.

An example of a mean difference map for the northern hemisphere generated from daily difference maps of the DFSC and the MOD10_L2 products for the winter season 2003/04 is shown in Figure 2.1.8.

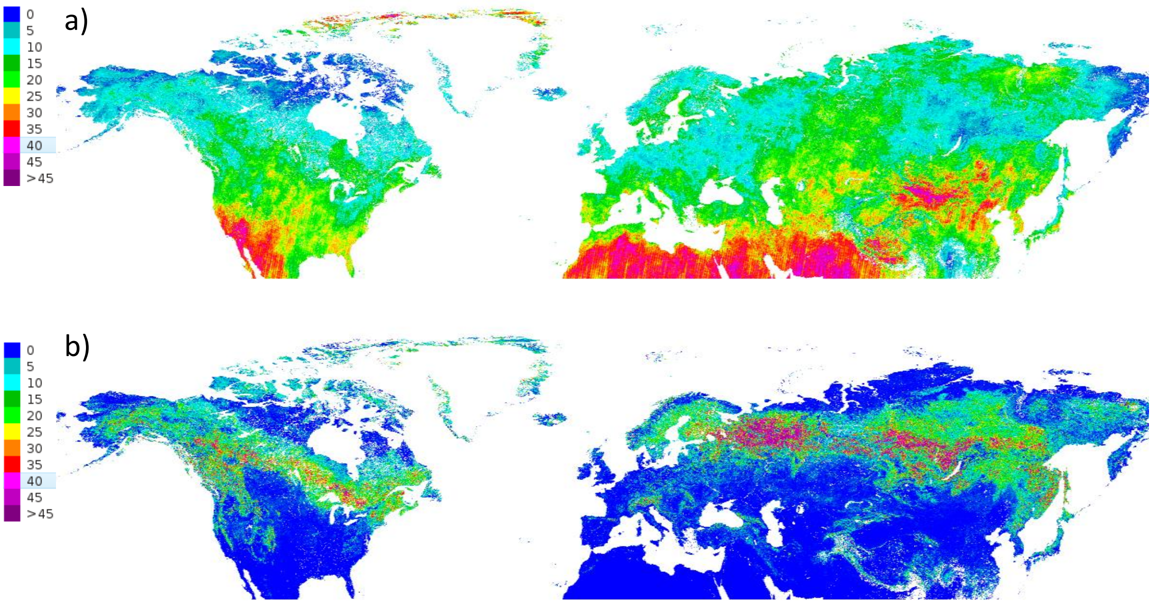


Figure 2.1.8. a) Number of pixels with differences in FSC for the period 1st October 2003 – 31st May 2004. b) Mean absolute deviation of the daily snow difference maps for the total area generated from GlobSnow-2 SE v2.1 and MOD10_L2 products for the selected period.

2.1.6 Additional research activities within SE development

In addition to the research directly realized in the SE development and production, several research activities were conducted in GlobSnow-2 project. These efforts complement the understanding of the optical and infrared remote sensing of snow cover and are considered valuable in the further method developments.

2.1.6.1 Exploiting multi-frequency data for SE retrieval

A multi-spectral unmixing approach for detecting fractional snow cover was developed and implemented by ENVEO using MERIS and AATSR data as preparation for Sentinel-3

SLSTR/OLCI. The method benefits from the different frequencies on-board of the MERIS (OLCI) and AATSR (SLSTR) sensors, and the improved spatial resolution of the MERIS (OLCI) instrument. The approach has been successfully tested in selected regions with different environments on the northern hemisphere.

2.1.6.2 Bare-ground reflectance in mountain regions

The main objective of this study was to determine top-of-atmosphere reflectance values, representative of mountain land cover types, which might be used for bare-ground reflectance parameterisation in a snow retrieval algorithm. The study applied terra MODIS reflectance data.

The bare-ground reflectance values we seek are those present under fractional snow cover conditions. This was done by retrieving bare-ground reflectance values as soon as the snow had melted. To determine the time when the snow just had completely melted on a per-pixel basis, we have used an algorithm developed by NR to analyse and interpret time series of reflectance observations.

We here determined average reflectance for a selection of regions where the inter-region reflectance might differ due to different regional vegetation, geology and climate. The reflectance was further stratified into the dominating land-cover classes for each region to cope for within-region variability. Four regions were chosen for the study: Scandinavian Mountains, Caucasus Mountains, Tibetan Plateau and Rocky Mountains. The first two turned out to have quite similar bare-ground reflectance statistics, despite quite different climates and geology; while the two latter have quite different bare-ground statistics from each other and from the first two regions. Figure 2.1.9 shows area-weighted mean reflectance values for the regions.

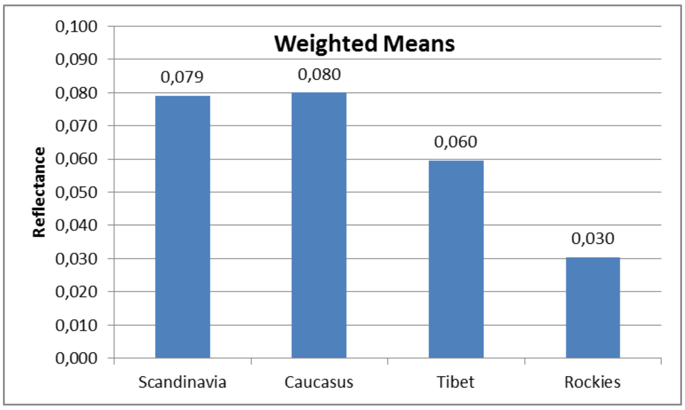


Figure 2.1.9 Area-weighted mean reflectance values for the four mountain regions studied.

One should keep in mind the uncertainty associated with the results, both temporally and spatially. Moisture is known to reduce surface reflectance, in particular in the case of soil moisture. This is probably the largest source of temporal short-term variability. Furthermore, there is some reflectance uncertainty associated with the timing of snow-free ground determined and the vegetation development. Some species start greening already before all the snow is gone locally. There might also be small patches of snow left that were undetectable. In mountain regions cast shadows play a significant role affecting the apparent TOA reflectance. The cast-shadow pattern will change with the increasing solar elevation during the snowmelt period. This means that there might be some deviation between the bare-ground reflectance found post-snow season and the apparent reflectance during the snowmelt period when the ground is covered with patches of snow (FSC < 100%).

2.1.6.3 Estimation of product uncertainty for mountain regions

The main effects creating uncertainty specific for mountains are reduction of measured reflectance due to cast shadows and residuals of the radiometric topographic correction. The cast shadows may be at a sub-pixel level due to small-scale terrain variations, or include several pixels.

To determine whether there was a bias for mountains associated with the methodology used to estimate uncertainty in the plains, we have studied two cases of mountain regions in Norway where we had access to SPOT-5 images, representing high enough spatial resolution to determine the actual snow cover (which turned out to be 100% in both cases). The results showed that the bias of the products is very small even for regions with very low shaded-relief values. Based on our very preliminary study, the need for bias correction may not be needed.

This indicates that the approach for uncertainty estimation used for plains might work for mountains as well. However, we do not know how it will work with stronger terrain relief (e.g. the Alps) or for patchy snow conditions. To make a sound conclusion possible, very-high resolution data to determine the true FSC would be needed for cases of patchy snow cover and stronger terrain relief.

If further investigation of the of uncertainty in mountains leads to the conclusion that the FSC retrieval results are unbiased with respect to the terrain effect and independent of the true fractional snow cover, the same uncertainty model as for plains can be applied everywhere. This is certainly the most attractive solution as the uncertainty estimates for the Snow Extent product would be seamless and consistent between plains and mountains.

2.1.7 The snow extent team

The algorithms, processing chains and products have been jointly developed by ENVEO, FMI, GAMMA, NR, SYKE and UniBe. In GlobSnow-2, SYKE coordinated the SE development and conducted the research work related to *SCAmod* method and transmissivity generation. Snow-free ground reflectance map is a result of the joint effort by SYKE and FMI. SYKE also developed the cloud masking algorithm *SCDA2.0*, in co-operation with FMI which implemented several test codes and took care of the data intermediate data processing. As part of the full intercomparison and evaluation of the SE v2.1 product data set, led by ENVEO, ENVEO assessed the performance of the SE products by intercomparing them with other snow products from other Earth Observation data. UniBe conducted research related to AVHRR-based snow mapping (*AVHRR_SPARC* and *AVHRR_SCAmod*) and developed a NRT-processing chain for daily snow cover maps of Europe considering their own AVHRR receiving facilities. Furthermore, UniBe led the preliminary validation work (DEL-11) and contributed to the final SE product validation. SYKE, NR, MeteoSwiss and ZAMG contributed to SE product evaluation/validation, led by ENVEO. NR and ENVEO also conducted research work related to the (multispectral) snow mapping in mountain areas. FMI carried out the processing of the historical time series and operates the near-real-time system for daily updates to the product time series. Development of VIIRS-based SE products and processing chain was a common effort of FMI, SYKE and GAMMA.

2.2 Snow Water Equivalent

The GlobSnow-1 and -2 projects have developed a long term data record of SWE products covering the non-alpine Northern Hemisphere, based on a time series of Nimbus-7 SMMR, DMSP F8/F11/F13/F17 SSM/I(S) observations and ground-based weather station measurements from 1979 until present. There are three SWE products (all in the EASE-Grid; Armstrong and Brodzik, 1995):

- **Daily Snow Water Equivalent** (Daily L3A SWE), snow water equivalent (mm) for each grid cell for all evaluated land areas of the Northern Hemisphere.
- **Weekly Aggregated Snow Water Equivalent** (Weekly L3B SWE), calculated for each day based on a 7-day sliding time window aggregation of the daily SWE product.
- **Monthly Aggregated Snow Water Equivalent** (Monthly L3B SWE), a single product for each calendar month, providing the average and maximum SWE, calculated from the weekly aggregated SWE product.

Examples of the daily and weekly SWE products are shown in Figures 2.2.1 and 2.2.2.; example of an uncertainty product is shown in Figure 2.2.3.

The GlobSnow-1 project resulted in two versions of the data record, SWE v1.0 and SWE v1.3. The dataset produced in GlobSnow-2 is identified as the GlobSnow SWE v2.0 data record.

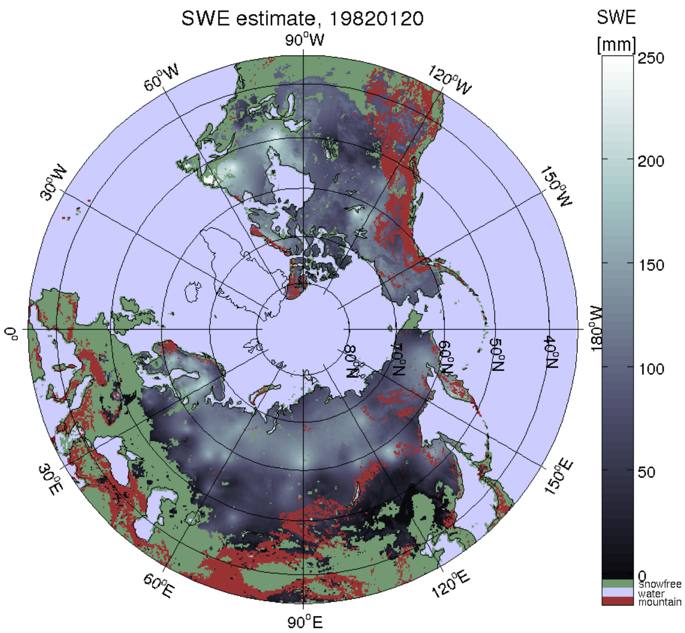


Figure 2.2.1: Example of a daily SWE product for 20 January 1982.

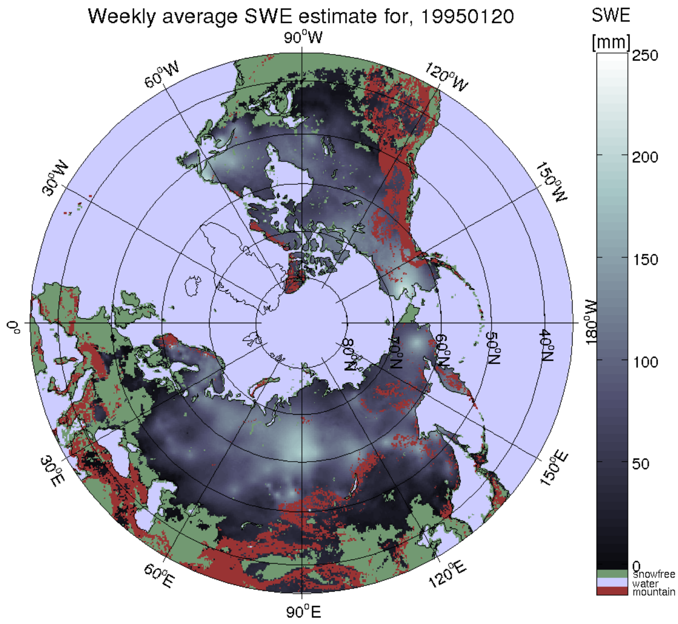


Figure 2.2.2: Example of a weekly aggregated SWE product for 20 January 1995.

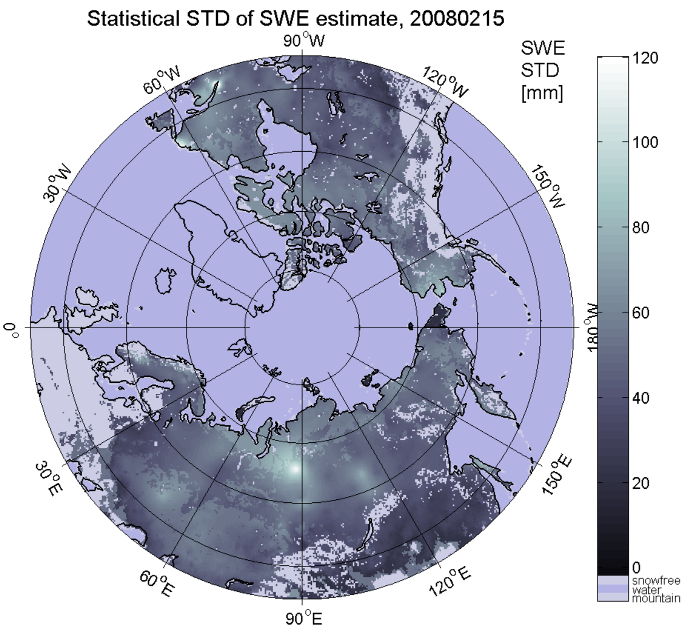


Figure 2.2.3: Statistical standard deviation of SWE estimate for 15 February 2008.

In addition to the SWE retrievals, the SWE products include information on the overall extent of snow cover. The information on snow extent is included in the product by utilizing the following coding for the SWE product, whereby SWE values of:

- 0 mm denotes snow-free areas (Snow Extent 0%)
- 0.001 mm denote areas with melting snow (Snow Extent undefined between 0% and 100%; no SWE retrieval because of the wet state of the snow cover)
- > 0.001 mm denote areas with full snow cover (Snow Extent 100%)

The areas that have been flagged as snow-free or melted are identified using a time-series melt detection approach described in Takala et al. (2009). The areas that are identified as wet snow or have no SWE retrieval, but are identified as snow covered with the time-series melt-detection approach, are denoted with a SWE value of 0.001 mm. The areas that are determined as snow-free or melted by the melt-detection approach, are denoted with a SWE value of 0 mm. All the other areas show a retrieved SWE value (that is in all cases greater than 0.001 mm).

The weekly (7-day) aggregated product is calculated using sliding window averaging: the SWE estimate for the current day is calculated as a mean of the samples from the previous 6 days and the current day (for each grid cell). The monthly aggregate, a single product for each month, is calculated by determining the mean and the maximum of the weekly SWE samples.

2.2.1 Algorithm and processing system

The SWE production system utilizes a SWE retrieval methodology (Pulliainen 2006) complemented with a time-series melt-detection algorithm (Takala et al. 2009) refined during the GlobSnow-1 and -2 projects and presented in detail in Takala et al. (2011) and (GlobSnow-2 SWE ATBD). The methodology produces SWE maps incorporated with information on the extent of snow cover at a coarse resolution (25 x 25 km grid cells). An additional output of the SWE retrieval method is uncertainty information at the grid cell level. The GlobSnow SWE processing system applies satellite-based passive microwave measurements and weather station observations collected by ECMWF in an assimilation scheme to produce maps of SWE estimates (in the EASE-Grid projection) over the northern hemisphere, covering all land surface areas with the exception of mountainous regions, glaciers and Greenland. As described in detail in Takala et al. (2011) and (GlobSnow-2 SWE ATBD), climate station measurements of snow depth, satellite passive microwave measurements, and forward simulations with a semi-empirical snow emission model are combined to estimate SWE.

The RMSE-values (uncertainty estimates) for SWE estimates include both the effect of the systematic (bias) and statistical (random) error as described in the GlobSnow-2 SWE Algorithm theoretical basis document (GlobSnow-2 SWE ATBD). Statitistical error is determined through an adaptive dynamic error propagation approach (Pulliainen, 2006; Takala et al. 2011). The systematic error is derived from the multi-year analysis of independent snow course observations from Russia and the Former Soviet Union (161 000 INTASS SCONE observations from 517 snow courses distributed in Eurasia), an example of the uncertainty estimate for a single product (15 February 2008) is show in Figure 2.2.3.

The SWE production system was implemented on the FMI operated Cray XT5m super computer environment for production of the 35-year time series. The processing of the long term dataset was automated within the Cray environment and requires slightly over a month of processing time to produce a version of the full data record.

2.2.2 Evaluation and validation activities for the SWE product

The original SWE algorithm evaluations during GlobSnow-1 project, concerned the GlobSnow v.0.9 Prototype product set, the v1.0 and v1.3 Full Product Set (FPS), are still relevant as the datasets continue to be distributed, but are not discussed in detail in this document. However, in general the retrieval accuracy of the various GlobSnow datasets are of the same order, around 32mm for SWE values below 150mm and slightly above 40mm for all assessed samples; there is no dramatic difference in actual retrieval performance between the various datasets, but the general consistency and data coverage (especially temporal extent) has been improved for the more recent GlobSnow SWE datasets, such as the v2.0 FPS which has resulted from GlobSnow-2 efforts. Additionally, some reported issues (Hancock et al. 2013) evident in earlier products (such as appearing and disappearing deep snow observations borne from sporadic weather station observations) have been mitigated in the latest v2.0 FPS. Validation activities conducted during the GlobSnow-2 project using the v2.0 FPS are briefly summarized here.

The successful production of the final long-term SWE v2.0 FPS starting from the fall 1979 through 2014 allowed for an extensive long-term assessment of the SWE retrievals. The availability of continuous reference data (snow course data) for Eurasia starting from before 1979 and extending until 2009 allowed for an evaluation of the SWE algorithm performance over thirty consecutive years.

The reference dataset contains snow course measurements collected across the former Soviet Union and Russia extending from 1979 until 2009. The measurements, carried out at 1264 different snow survey locations, range from 35° to 85° northern latitude and 14° to 179° of eastern longitude and contain 163,300 samples (146,200 samples with SWE below 150mm threshold). This vast dataset, compared against the GlobSnow SWE data for the same period, was suitable for identifying any retrieval issues with data acquired from different passive microwave sensors, across different geographical regions, or from different periods of time. The RMS-errors and biases, calculated independently for each year for the long term dataset is shown in Figure 2.2.4.

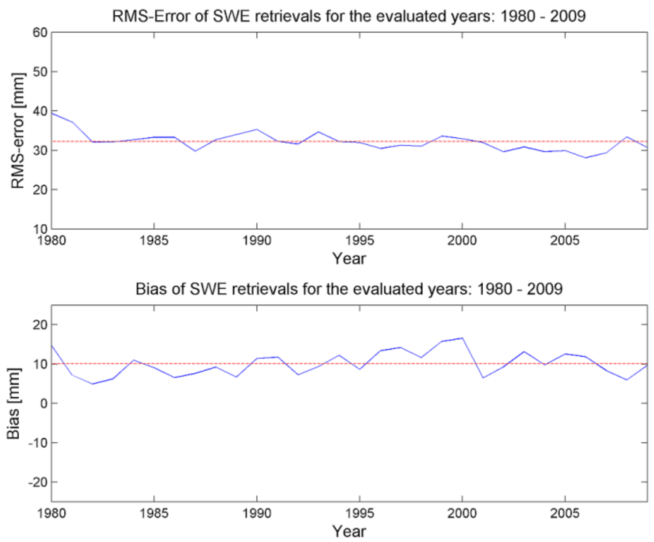


Figure 2.2.4, The RMS-errors and biases shown for the years 1980 to 2009 for SWE v2.0 FPS dataset. SWE estimates compared with snow path measurements from Russia and former USSR. The evaluated dataset with SWE values below 150 mm contains more than 146 200 samples. The average RMS-error and bias is shown with red dashed line.

The evaluations carried out for the GlobSnow SWE v2.0 FPS (Full Product Set) utilized the weekly aggregate SWE product that was compared with the Russian snow course data. The results show a good agreement between the retrievals and reference data. The comparison showed that the RMS error for reference SWE values ranging between 0–150 mm, (through the years 1979–2009, consisting of 146,200 samples) was 32.5 mm. The bias for the same dataset was +9.8 mm. Consideration of all the samples of the full dataset (all SWE values, consisting of 163,300 samples) showed a bias of +2.3 mm and RMS error of 43.5 mm (both values are a significant improvement over the alternative evaluated algorithms, based solely on satellite passive microwave measurements; as described in full in GlobSnow-1 deliverable D-1.7). The results for this comprehensive Eurasian reference dataset are very similar to those carried out using data from Finland and across Canada for both v2.0 FPS and earlier GlobSnow evaluations (reported in GlobSnow-1 deliverables D-1.7, D-1.9, and D-2.5; and GlobSnow-2 DEL-21a) and show no significant issues with the SWE retrievals.

2.2.3 The snow water equivalent team

The algorithms, processing chains and products have been developed jointly by FMI and EC. FMI has had the coordinating role of the SWE development, assisted by EC in all aspects of the work including algorithm development and refinement, the extensive validation efforts, planning for the data production and continuous development activities.

2.3 GlobSnow near-real time processing system

The GlobSnow Processing System (PS) produces the GlobSnow Snow Extent (SE) and Snow Water Equivalent (SWE) products from satellite (SE and SWE) and synoptic weather station (SWE) data. The PS is modular and can run on any UNIX flavored Operating System. Within the project, the PS is running on two separate platforms to better deal with the different needs of long-term data processing and near-real time production. The historic data products are processed on the FMI Cray XT 5m supercomputer using parallel processors and access to the large input data archive. The near-real time (NRT) products are produced on a dedicated multi-core Linux server with fast Internet connection. The NRT PS runs autonomously and checks the data provider archives for new input data on a regular basis. Both implementations produce daily products. Aggregation is done on a weekly (last 7 days) and monthly (calendar month) base. All products, historic and NRT, are made immediately available to users through the GlobSnow website www.globsnow.info.

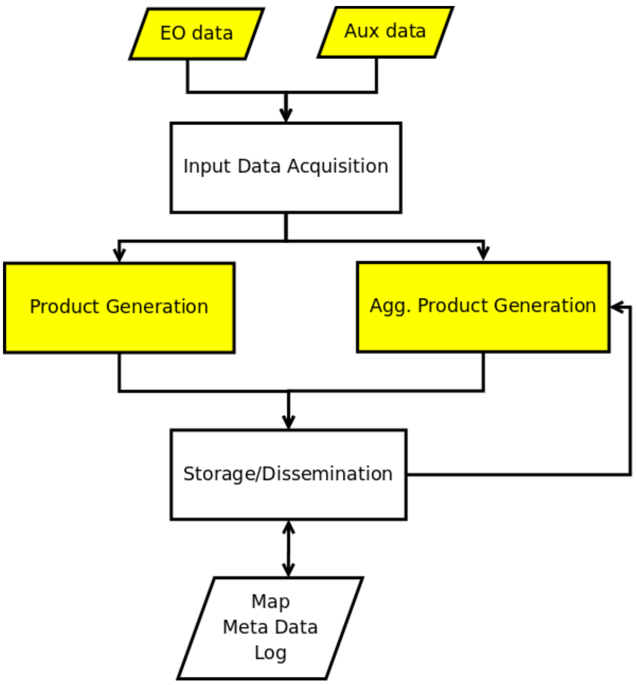


Figure 2.3.1: Generalized processing chain architecture.

The GlobSnow products are provided in netCDF format that follows the CF (Climate and Forecast) version 1.1 Metadata Convention. This format is also consistent with recent recommendations for ESA CCI products providing history and UUID (universally unique identifier) information. For easy browsing of the product archives, maps in PNG image format and quick-look images in JPEG format are also provided. Additional information on the products and the developed processing systems are given in Table 2.1.

Within Globsnow-2 the PS was further developed. The development was driven on the one hand by new research results and needs, and on the other hand by technical needs to reduce the processing time and integrate new sensors. While it was foreseen to run the NRT processing on AATSR data, the strategy had to be changed after Envisat failed in April 8, 2012. VIIRS was selected as a replacement sensor, resulting in a major development effort to have the VIIRS NRT processing implemented for the winter 2012/13.

To optimize the processing time, the PS orthorectification module was redesigned, the BEAM dependence dropped and re-implemented. The new orthorectification module reduced processing time significantly.

Another improvement was gained by porting the code to take advantage of multi-cores. A major development was necessary for the improved cloud handling. New algorithms were implemented as well as a flexible cloud convolution processor. Support for several *SCAmod* algorithms was implemented to be able to produce time serieses for assessment purposes. Furthermore the new uncertainty algorithm was implemented and a layer indicating cloud free observations in the monthly product was added.

Table 2.1 Description of the SE / SWE products and production systems.

	SE	SWE
Implementation	ANSI-C. The initial version that was coded based on an IDL prototype was further developed and improved.	Running prototype, based on the compiled Matlab code of the development version.
Input data	ERS-2 ATSR2 / Envisat AATSR / Suomi NPP VIIRS	SMMR / SSMI / SSMIS Synoptical weather data
Auxilary data	Mountain mask Water mask Forest mask Glacier mask Transmissivity mask DEM	Mountain and glacier mask Water mask Forest cover data
Size of input data	5 GB / day	4 MB / day
Size of output data	15 MB / day	3.3 MB / day
Processing time on NRT	30 minutes from data downlink	30 min / day
Projection	Lat/Lon WGS 84	EASE-Grid North
Pixel spacing	0.01 deg. x 0.01 deg.	25 km x 25 km

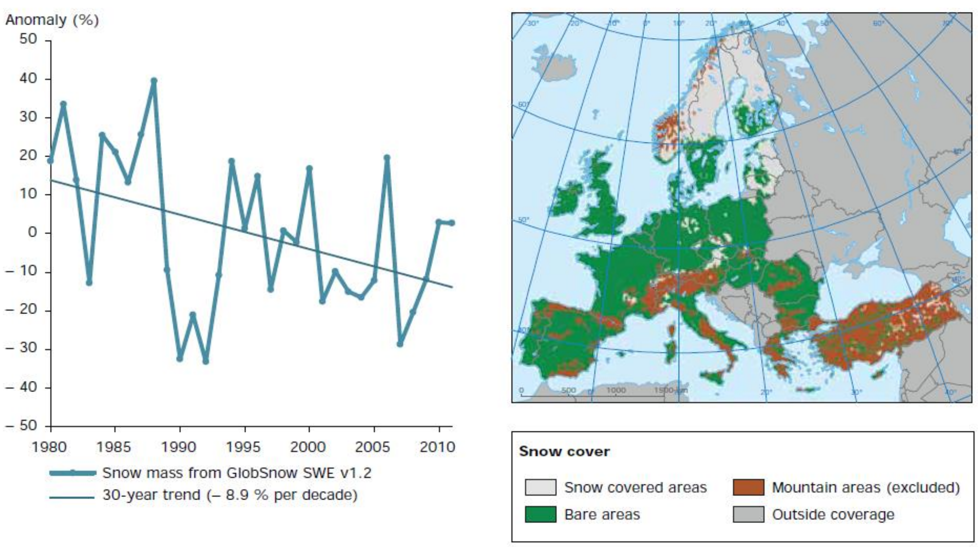
3 INTERACTION WITH END-USER COMMUNITY AND DATA DISSEMINATION

3.1 Utilization of GlobSnow data and data dissemination

The melt algorithm developed and applied for GlobSnow SWE retrieval, described in Takala et al. (2009) was cited and used as a source for the IPCC 5th Assessment report (2013).

The GlobSnow SWE v1.2 data record was applied in *"Climate change, impacts and vulnerability in Europe 2012"* an European Environment Agency (EEA) report to portray the changes in snow conditions for the European domain for the years 1980 - 2011, shown in Figure 3.1.1.

Figure 2.11 Trend in March snow mass in Europe (excluding mountain areas) (1980–2011)



Note: Left: Anomalies for March snow mass and the 30-year linear trend in the EEA region (excluding mountain areas).
Right: Snapshot of snow cover on 15 February 2009.

Source: GlobSnow (http://www.globsnow.info) (Luojus et al., 2011).

Figure 3.1.1 GlobSnow data was used in the "***Climate change, impacts and vulnerability in Europe 2012***", an indicator-based report, EEA Report, No. 12/2012. ISBN 978-92-9213-346-7, ISSN 1725-9177, doi:10.2800/66071, EEA, 2012.

The GlobSnow SWE product is utilized by the World Meteorological Organization (WMO), Global Cryosphere Watch (GCW) initiative to provide a daily near-real time tracker of hemispherical snow conditions. The tracker presents the status and progress of total terrestrial snow mass, set in context with regard to the 35-year historical climatology for the Northern Hemisphere. The tracker is updated daily and is available on the www.globalcryospherewatch.org website.

GlobSnow SWE data have been applied in the European Joint Research Centre (JRC) Drought Observatory as a drought indicator, titled "Standardized Snow Pack Index".

GlobSnow SWE data are being distributed along the other well-established cryosphere datasets within the National Snow and Ice Data Center (NSIDC), Boulder, Colorado. The inclusion of GlobSnow SWE dataset to the NSIDC catalog discontinued the distribution of some earlier SWE datasets that were based solely on satellite-derived methodologies.

The limited utilization of GlobSnow SE data to date is partially due to a limited spatial coverage of the daily data (due to the narrow swath of A/ATSR sensor). The end-users have expressed desire to a full daily coverage, which has been available from MODIS-based data records, although with a shorter time span, as MODIS onboard the Terra satellite initiated data acquisition on February 2000 (ERS-2 ATSR-2 record starts in July 1995). However, it has been clearly shown that the *SCAmod* approach, used for the GlobSnow SE data record is useful in many applications; such as for the determining of Growing Season Start Day (GSSD) on the boreal forest zone as shown in Böttcher et al. (2014) and for the determination of energy balance of tundra regions as demonstrated in Cohen et al. (2013).

The near-real time data processing and dissemination, established in the ESA DUE GlobSnow-1/2 projects will be continued by FMI for the foreseeable future. The potential to migrate the NRT SE & SWE services to the EUMETSAT H-SAF framework will be investigated. The production of the long term datasets will not continue at the present. The data dissemination of all produced GlobSnow SE and SWE data sets will be operated and maintained on the current, dedicated, GlobSnow servers, located at the Sodankylä National Satellite Data Center part of the Finnish Meteorological Institute, Arctic Research Centre.

3.2 End-user interaction and user consultation

The GlobSnow project was able to gather a large end-user community, consisting of scientists, data providers, satellite agencies, and various end-users interested in water resource management, climate change, numerical weather prediction, hydrological forecasting and everyday people interested in seasonal snow cover information. The GlobSnow data policy, based on principle of open and free data, allowed unrestricted and unlimited access to all the GlobSnow data for any interested party. For advanced users, looking to download the entire long term data records at once, a dedicated ftp-server was set up, allowing the users to gain an easy access to the full datasets, free of charge.

The GlobSnow activities were widely presented to end-user community within several conferences during the GlobSnow-1 and GlobSnow-2 projects. Many talks were given at international conferences but of special interest were the contributions of members of the GlobSnow consortium at workshops, where they widely used the possibility to interact with a wide variety of end-users. Of particular interest were the Snow and Land Ice workshops of the European Association of Remote Sensing Laboratories, which took place in Bern, Switzerland in 2011 and 2014. Special half-day sessions were dedicated for GlobSnow presentations and official slots for user interaction were arranged. The feedback of users and interested colleagues (e.g. from UK MetOffice, Eumetsat, Potsdam Institute for Climate Impact Research, Hydrological services etc.) gathered during these events were of great value for the GlobSnow team to tailor the products as needed. Furthermore, the products, their retrieval approaches and their accuracies were presented to the community, which further resulted in increased access rates at the GlobSnow data server. The program and the presentations of the EARSeL 2014 workshop are accessible at http://www.earsel.org/SIG/Snow-Ice/workshop/programme.php.

The Global Cryosphere Watch workshop in Toronto (2013) was a great opportunity for the GlobSnow team to present the retrieval algorithms and products to colleagues of NOAA, NASA, WMO, and Environment Canada. This workshop also provided the motivation for a new ESA-led initiative - the Satellite Snow Products Intercomparison & Evaluation Exercise (SnowPEx) for the systematic comparison of global snow products. The first SnowPEx workshop was held in July 2014, and GlobSnow members have leading roles in the planned comparisons of SE and SWE products.

3.3 White Paper on “Perspectives for a European Satellite-based Snow Monitoring Strategy”

The GlobSnow consortium was involved in drafting a community-wide white paper on future perspectives for a European Satellite-based Snow Monitoring Strategy. The aim of the white paper is to set out recommendations to space agencies, international and national institutions and decision makers responsible for decisions regarding strategic and financial issues. The White Paper also identifies future challenges, opportunities and needs regarding satellite-based snow services and product development within European and global frameworks over the next decade. The White Paper provides a short overview on the current status of satellite-based snow services and products, identifies gaps with respect to user’s needs, and discusses requirements for future R&D and snow services.

The White Paper refers to ongoing programmes and initiatives with the intention of improving coordination within and between communities involved in monitoring, developing, disseminating and implementing satellite-based snow products. The summary of current user’s needs, and gaps in needs regarding satellite-based snow services and products are based on user consultation workshops, review processes within the snow community, and literature.

The following needs for progress towards a Satellite-based Snow Monitoring Strategy for the benefit to the users were identified during the drafting process:

- Establish a cross-continental Group on Satellite Snow Monitoring Perspectives.
- Improve the user-interaction in all product phases from the development phase to data dissemination for a better user acceptance of satellite-based snow products.
- Perform regular product intercomparison, validation and product assessment exercises (e.g. WMO GCW endorsed ESA SnowPEX project), coordinated within the community.
- Communicate and provide quantified product uncertainties following common definitions and establish rules and procedures in consultation with the end-users.
- Consider and assure in time a transfer from R&D products and services into future sustainable initiatives to guarantee a continuity for the end-users.
- Promote successful demonstration projects and pilot-products through various channels to exploit the improved capabilities of new EO sensors in the upcoming national and international space programmes.

The White Paper, available on the GlobSnow website, provides a high-level description and identifies what should be done to better meet users’ needs with upcoming new satellite infrastructure and what role funding agencies, users and the entire community could play.

4 CONCLUSIONS

4.1 Snow Extent

The Snow Extent (SE) Full Product Set (FPS) Version 2.1 for the Northern Hemisphere contains information on snow cover fraction retrieved from ERS-2 ATSR-2 and Envisat AATSR from 1995 until present. There are four products: Daily Fractional Snow Cover (DFSC), snow fraction (%) per grid cell for all satellite overpasses on a given day; Daily 4-classes Snow Cover (D4SC), snow cover classified into four categories per grid cell for all satellite overpasses on a given day; Weekly Aggregated Fractional Snow Cover (WFSC) for all satellite overpasses within a 7-day period based on aggregation of daily products; and Monthly Aggregated Fractional Snow Cover (MFSC) for all satellite overpasses within a calendar month.

The *SCAmod* method used to produce the GlobSnow SE products is a relatively new approach for the hemispheric-scale FSC retrieval. Although it is capable of detecting FSC also in areas of relatively dense forest cover, the achieved accuracy may vary according to the land-cover. For example, there are potential inaccuracies originating from the forest compensation over very dense canopy (dark target with a very low transmissivity), since a minor increase in observed reflectance (for instance, due to the atmospheric aerosols) will lead to an overestimated FSC. Also the dependency of *SCAmod* on the (static) land cover data makes it sensitive to the changes in land-cover over time not captured by the GlobCover data (of static nature). However, despite these weaknesses, the various evaluation activities indicate that GlobSnow SE product (v2.0 and v2.1 as produced within GlobSnow-2) provides generally high-quality FSC and, importantly, detects fractional snow in forests better than the other, alternative, continental/global scale products available.

It should be noted that the GlobSnow implementation of *SCAmod* is optimized for springtime (ablation) conditions, which is evident from the way the parameters are determined. This is further emphasized by the conservative limit applied for the sun zenith angle (max. 73° is accepted) in GlobSnow SE production, which limits the mapped area quite drastically during the late accumulation period and the high snow season in northern latitudes. However this limitation is not crucial for snow mapping during the melting period in boreal forest and tundra zones and has no impact on mid-latitude snow retrieval.

The GlobSnow SE daily products DFSC/D4SC are characterized by data gaps due to the narrow swath width (~500 km) of the ATSR-2 and AATSR sensors. This, together with the 3 days revisit time, means that the number of observations used in the development of weekly and monthly composites is limited. This weakens the ability of these products to capture high temporal changes (snow deposited and melted in a period of a few days).

Regardless of these limitations, The GlobSnow SE product is the first hemispheric, daily, moderate resolution record on the fraction of snow cover that has been produced utilizing the ESA ATSR-2 and AATSR sensor records. It differs from the other available products due to the specific treatment of forests using a reflectance model based approach. The GlobSnow SE dataset complements the previous records generated with greater temporal coverage but a lower spatial resolution (AVHRR 1980-2011) and records with similar resolution but a shorter temporal extent (MODIS 2001-2011) and is a unique dataset for enhancing our understanding of historical snow conditions. Finally, the first analyses of the SE based on NH VIIRS data – providing daily global coverage without data gaps, indicate a good potential of *SCAmod* method to capture the spatial and temporal variation and trends in the fractional (melting) zone in particular. This is due to *SCAmod* providing FSC directly, not through aggregation from the binary ('snow/'non-snow') data which usually leads to biased FSC (Metsämäki et al., 2014).

The intercomparison with binary and fractional snow information from other satellite data and in-situ measurements show mean differences in the order of about 10 % FSC, with mean Bias values between -3.5 and 3.5, and mean standard deviations of about 25 %. In general, major deviations between the DFSC and other snow maps were found in forested mountainous areas, while the products match usually well in plain non-forested areas.

Open methods and protocols for intercomparison of various existing hemispheric snow products are currently developed in the ESA funded project "SnowPEx – Satellite Snow Product Intercomparison and Evaluation Experiment" (SnowPEx, 2014). This project, backed up by WMO / Global Cryosphere Watch and WCRP-CliC, elaborates guidelines for generation of reference data sets and for intercomparing and validating satellite snow products. Further activities include the evaluation of the quality of current snow products generated by various international providers, and the elaboration of guidelines for product improvement.

4.2 Snow Water Equivalent

The GlobSnow Snow Water Equivalent (SWE) v2.0 full product set (FPS) for the Northern Hemisphere provides information on SWE retrieved from SMMR and SSM/I(S) passive microwave sensors, combined with ground-based weather station data, from 1979 until 2014. It is the first satellite-based daily SWE dataset at a hemispheric scale (non-alpine) that spans 30+ years. Based on the extensive validation efforts conducted within the GlobSnow-1/-2 projects, the product shows a consistent performance with stable uncertainty characteristics over the whole 30+ years of record, and represents a noted improvement over other existing SWE products based solely on satellite passive microwave measurements. For cases when SWE < 150 mm (approximately 88% of the reference data used for validation) RMSE is 32.5 mm, which is under the target accuracy of 40 mm.

The SWE processing system applies satellite-based passive microwave measurements and weather station observations (collected by ECMWF) in an assimilation scheme to produce maps of SWE estimates (in EASE-Grid format) over the northern hemisphere, covering all land surface areas with the exception of mountainous regions, glaciers, and Greenland.

The SWE v2.0 FPS spans the Northern Hemisphere for years 1979 to 2014. The product includes: daily (L3A) SWE data and quick-look images, weekly and monthly (L3B) aggregated SWE data and the corresponding quick-look images. In addition to the SWE data, information on the SWE uncertainty (error estimates) is provided with the dataset (GlobSnow-2 SWE ATBD). The data are available through both the LitDB FTP server and a web-based data dissemination site.

A daily near real time (NRT) service capability with a latency of one and a half days was also developed, with the data provided to users through the FMI ftp- and www-servers.

5 RECOMMENDATIONS

5.1 Snow Extent

In validations/evaluations, GlobSnow SE has proven to provide FSC with a reasonable accuracy. *SCAmod* method employed in the FSC provision relies on a simple radiative transfer based reflectance model. Although there are other more complicated and locally adjustable reflectance models that could be used, the requirement of simplicity and – above all – the application area of the Northern Hemisphere, strongly support the current formulation. *SCAmod* method could however be enhanced to better account for spatial and temporal distribution of the applied parameters. The way towards this is already realized as the spatially varying snow-free ground reflectance; but there are also other parameters that could be adjusted. Snow-free ground reflectance could vary according to the sun zenith angle. Also there are plans to modify the NDSI-thresholding for detecting the confident snow-free conditions. The snow-free ground reference reflectance map could be improved by extending the current applied data set for calculating the statistics for different land cover classes; also temporal evolution could be assessed and used to establish a temporally varying map. The transmissivity map could be improved in the future, in regard to the way the class-stratified transmissivity statistics are generated, including the handling of global albedo data.

The uncertainty information of the SE products can be improved by further investigating the statistical characteristics of the parameters of *SCAmod* (reflectances of snow-free ground, wet snow and opaque forest canopy, and forest canopy transmissivity). This would improve the consideration of the statistical FSC estimation error (the current product uncertainty layer). On the other hand, information on the systematic errors of FSC estimates is not provided at the moment. The inclusion of this error contribution would require extensive validation activities with independent ground truth reference data. Until now, this has been possible only within Finland, implying that the gained systematic error is not necessarily representative for other geographical regions.

As mentioned above, GlobSnow SE data record is the first hemispheric daily snow cover data set generated from ESA ATSR-2 and AATSR observations, but introduces data gaps due to the sensors' limited spatial coverage. In GlobSnow-2, the SCAmod method for FSC retrieval was tested for the historic time series of AVHRR data. The results of this exercise for the European area are very promising and encourage us to extend the AVHRR-based snow mapping with *SCAmod* to cover the Northern Hemisphere. This would be an remarkable effort and would result in a novel long-term dataset providing direct sub-pixel fractional snow cover (not conventional binary snow/non-snow) information to be used in climate studies (→ towards a FCDR to be developed and compiled in a future ESA CCI snow project). This dataset would also be beneficial for the development and generation of a fused SE&SWE product since this fusion is most successful whenever SWE-retrievals are complemented by fractional snow information with full spatial coverage. Additional recommendations include the generation of a bare ground reflectance map with consideration of the contribution from the atmosphere and inclusion of the latest development of "ESA CCI cloud" -project to improve cloud detection algorithm.

5.2 Snow Water Equivalent

Recommendations for the future Snow Water Equivalent algorithm development efforts include the following areas:

a. Assessment and incorporation of an improved HUT snow emission model for SWE retrieval needs to be a key focus area in the future. Improved brightness temperature simulations will improve the overall accuracy of the GlobSnow retrievals, particularly in regions with sparse conventional observation networks. Recent work includes consideration of additional landscape components (such as lakes; Lemmetyinen et al., 2011), the evaluation of HUT performance using varying levels of sophistication for input data (Derksen et al., 2012; 2014) and evaluation of the microwave effective grain size parameter, produced in an intermediate step in the SWE retrieval (Lemmetyinen et al., in press).

b. Introduction of a temporally and spatially dynamic density to the GlobSnow SWE retrieval is important. At present, a relatively smooth spatial SWE distribution is characterized by GlobSnow compared to other gridded (non-Earth Observation) products. This issue is also linked to the lack of land cover consideration in the kriging of background snow depth and grain size fields within the retrieval processing chain. Extensive experimentation was conducted during GlobSnow-2 with no optimal solution yet decided.

c. Supplementary products in addition to the current SWE and SWE uncertainty fields could be developed, including integration of externally derived snow extent information, or synergistic use with other model derived SWE datasets (i.e. Brun et al., 2013)

d. Development of an ensemble suite of GlobSnow SWE products, using different retrieval parameterization and different or variable sets of input data; to improve the characterization of effects rising from utilization a variable input dataset for a multi-decadal dataset

The algorithm development work should also serve other initiatives related to the regional (higher spatial resolution) scale mapping of SWE, especially the H-SAF development of EUMETSAT.

Other important topics for the future research and analysis should consider issues that are essential for the production of reliable hemispheric Climate Data Records on SWE:

- Conduct an assessment of the impact of inter-sensor calibration issues that may affect the stability of the SWE product, specifically the switching of input radiometer data between SMMR, SSM/I(S) (various sensors on various platforms) and AMSR-E sensors.

- Conduct a more detailed evaluation to determine the impact of variability in the number/spatial density of weather stations used in the assimilation scheme on the spatial pattern of SWE retrievals. One approach would be to provide an ensemble of SWE estimates using varying climate station inputs, such as only those stations that meet requirements for consistency and continuity of reporting, and a ‘satellite only’ retrieval that does not include the assimilation of a background snow depth field from weather station observations. The impact of the transition from manual to auto stations in many countries during the 1990’s should be determined through a focussed regional analysis. For instance, the metadata are available to investigate this issue using climate station observations from Canada.

- It is necessary to evaluate the agreement of the GlobSnow SE and SWE snow extent estimates, and develop methodologies for merging of SWE and SE products on a coarse spatial scale (25km EASE-Grid). Dry snow detection and snow extent mapping could be improved through the use of time series of radiometer data, the optically-derived GlobSnow SE products, and/or a fused SWE/SE dataset. Existing hemispheric snow extent datasets (i.e. the NOAA IMS snow charts or AVHRR-based datasets) could be used for validation, or as a source of snow mask information.

- To date, evaluation of the SWE product has focussed on the retrievals at the grid cell level. Further assessment of the SWE retrieval on different climate regions and varying geographical locales needs to be carried out. Inter-comparisons of alternative model-based SWE retrieval approaches should also be considered, e.g. ERA Interim, EC CMC, and ECHAM 5 GCM based SWE data could be compared with the GlobSnow SWE data.

6 PUBLICATIONS

The GlobSnow-1 and GlobSnow-2 projects resulted in several journal articles and a large number of abstracts and presentations in scientific conferences, listed below:

Published scientific journal articles:

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

- 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. doi: 10.1016/j.rse.2014.09.018.

- 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 Sens. Environ., 123: 508-521. doi: 10.1016/j.rse.2012.04.010.

- Salminen, M., Pulliainen, J., Metsämäki, S., Böttcher, K. & Heinilä, K. (2013). MODIS-derived snow-free ground reflectance statistics of selected Eurasian non-forested land cover types for the application of estimating fractional snow cover. Remote Sens. Environ., 138: 51-64.

- Pulliainen, J., Salminen, M., Heinilä, K., Cohen, J., Hannula, H.-R. (in press). Semi-empirical modeling of the scene reflectance of snow-covered boreal forest: Validation with airborne spectrometer and lidar observations. Remote Sens. Environ.

- Lemmetyinen, J., Derksen, C., Toose, P., Proksch, Pulliainen, J., Kontu, A., Rautiainen, K., Seppänen, J., and Hallikainen, M. (in press). Simulation of spatially varying snow cover brightness temperature using HUT snow emission model and retrieval of a microwave effective grain size. Remote Sens. Environ.

- Heinilä, K., Salminen, M., Pulliainen, J., Cohen , J., Metsämäki, S., Pellikka, P., (2014). The effect of boreal forest canopy to reflectance of snow covered terrain based on airborne imaging spectrometer observations. Int. J. App. Earth Obs. Geoinf., 27:31-41.

- Lemmetyinen, J. Kontu, A., Kärnä, J.-P., Vehviläinen, J., Takala, M., Pulliainen, J., (2011). Correcting for the influence of frozen lakes in satellite microwave radiometer observations through application of a microwave emission model. Remote Sens. Environ., 115(12): 3695-3706. doi: 10.1016/j.rse.2011.09.008.

- Kontu, A., Lemmetyinen, J., Pulliainen, J., Seppänen, J., Hallikainen, M. (2014). Observation and modeling of the microwave brightness temperature of snow-covered frozen lakes and wetlands. IEEE Trans. Geosci. Remote Sens., 52: 3275-3288.

- Derksen, C, Toose, P., Lemmetyinen, J., Pulliainen, J., Langlois, A., Rutter, N., Fuller, M.C., (2012). Evaluation of passive microwave brightness temperature simulations and snow water equivalent retrievals through a winter season. Remote Sens. Environ., 117:236-248.

- Derksen, C., Lemmetyinen, J., Toose, P., Silis, A., Pulliainen, J., Sturm, M. (2014). Physical properties of Arctic versus subarctic snow: Implications for high latitude passive microwave snow water equivalent retrievals. J. Geophys. Res. - Atm., 119: 7254-7270.

- Cohen, J., Pulliainen, J., Menard, C., Johansen, B., Oksanen, L., Luojus, K. and Ikonen, J., (2013). Effect of reindeer grazing on snowmelt, albedo and energy balance based on satellite data analyses. Remote Sens. Environ., 135:107-117. doi: 10.1016/j.rse.2013.03.029.

International conference presentations (regarding GlobSnow-2 project):

- Space for the Arctic ’12 conference, Copenhagen, Denmark, March 2012; invited oral presentation by K. Luojus

- European Geosciences Union, General Assembly 2012, Vienna, Austria April 2012; oral presentation by K. Luojus

- International symposium on Seasonal snow and Ice by International Glaciological Society, Lahti, Finland, May 2012; oral presentation by K. Luojus

- IEEE International Geoscience and Remote Sensing Symposium 2012, Munich, Germany, July 2012; oral presentation by K. Luojus

- Finnish National Remote Sensing days, Helsinki, Finland, October 2012; oral presentation by K. Luojus

- ESA Sentinel-3 OLCI/SLSTR & MERIS/(A)ATSR Workshop, ESRIN, Rome, Italy, October 2012; oral presentation by K. Luojus

- ESA/EGU/CLIC Earth Observation and Cryosphere Science Conference, ESRIN, Rome, Italy, November 2012; oral presentation by K. Luojus

- WMO Global Cryosphere Watch (GCW) “Snow Watch” meeting, Toronto, Canada, January 2013; oral presentation by K. Luojus

- European Geosciences Union, General Assembly 2013, Vienna, Austria April 2013; poster presentation by K. Luojus

- WMO Polar Space Task Group meeting, 22-23 May 2013, Paris, France, invited oral presentation (on snow remote sensing and GlobSnow) by K. Luojus
- IEEE International Geoscience and Remote Sensing Symposium 2013, Melbourne, Australia, July 2013; oral presentation by K. Luojus
- IEEE International Geoscience and Remote Sensing Symposium 2013, Melbourne, Australia, July 2013; oral presentation by M. Takala
- ESA Living Planet Symposium, 9-13 September 2013, Edinburgh, Scotland; oral presentation by K. Luojus
- ESA Living Planet Symposium, 9-13 September 2013, Edinburgh, Scotland; oral presentation by S. Metsämäki
- Finnish National remote sensing days, Espoo, Finland, 23 October 2013; oral presentation by K. Luojus
- Finnish National remote sensing days, Espoo, Finland, 23 October 2013; oral presentation by S. Metsämäki
- URSI Commission F Microwave Signatures 2013, Espoo, Finland, 28-31 October 2013; oral presentation by K. Luojus
- ESA LPVE Land product validation and evolution. 28 - 30 January 2014, ESA-ESRIN, Frascati; oral presentation by S. Metsämäki
- ESA LPVE Land product validation and evolution. 28 - 30 January 2014, ESA-ESRIN, Frascati; oral presentation by K. Luojus
- EARSeL LISSIG, 3-6 February 2014, Bern, Switzerland; several oral and poster presentations by the GlobSnow consortium [a dedicated session concerning ESA GlobSnow project]
- IEEE International Geoscience and Remote Sensing Symposium 2014, Quebec, Canada, 13-18 July 2014; poster presentation by S. Metsämäki
- IEEE International Geoscience and Remote Sensing Symposium 2014, Quebec, Canada, 13-18 July 2014; oral presentation by K. Luojus
- 1st International Satellite Snow Product Intercomparison Workshop, ESA SnowPEX, Washington DC, USA, 21-23 July 2014; oral presentation by S. Metsämäki
- 1st International Satellite Snow Product Intercomparison Workshop, ESA SnowPEX, Washington DC, USA, 21-23 July 2014; oral presentation by K. Luojus

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