Global Snow Monitoring for Climate Research

Final Report (FR)

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ABSTRACT:

This report presents an overview on the main activities and a synthesis of key results of the ESA GlobSnow project. The main objective of the project was the development and implementation 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 starting from 1995 and extending to the present. The satellite data applied to the generation of SWE products included measurements from two sets of sensors: SMMR and SSM/I (onboard the Nimbus-7 and DMSP F8, F11, F13 and F17 satellites) that form a continuous set of passive microwave observations starting from 1978 and continuing to the present.

Conclusions on the project activities and recommendations for further work are presented in the final sections 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)
ASAR	Advanced Synthetic Aperture Radar (instrument of Envisat)
AVHRR	Advanced Very High Resolution Radiometer (instrument of NOAA-satellites)
DDF	Design Definition File
DDS	Diagnostic Data Set
DJF	Design Justification File
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
FCDR	Fundamental Climate Data Record
FMI	Finnish Meteorological Institute
FSC	Fractional Snow Cover
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)
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

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1 INTRODUCTION

The main objective of the European Space Agency (ESA) Data User Element (DUE) funded GlobSnow project was the development and implementation 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 and adapting algorithms for the derivation 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, 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 this task. The satellite data utilized for generation of the SE product set included ESA operated ERS-2 ATSR-2 and ENVISAT AATSR records starting from 1995 and extending to the present. The satellite data applied for the generation of SWE product included measurements from two sets of sensors: SMMR and SSM/I (onboard the Nimbus-7 and DMSP F8, F11, F13 and F17 satellites) that form a continuous set of passive microwave observations starting from 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 on fractional snow cover that has been produced from ESA ATSR-2 and AATSR measurements. The GlobSnow SE dataset complements the previous records generated with greater temporal extent but a lower spatial resolution (AVHRR 1980-2011; Zhao and Fernandes, 2009) and records with similar resolution but a shorter temporal extent (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 northern hemisphere that extends over 30 years. The previous existing daily SWE records have spanned a shorter time period (2002-2011; Kelly, 2009) or described the snow conditions on a monthly basis for a similar period (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 (see GlobSnow Deliverable D-1.7 – Design Justification File).

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 develop within the project. The efforts of GlobSnow project are thoroughly documented in the project reports, and are listed in Table 1.1. The GlobSnow product set, all the documentation and the independent validation data are available at the GlobSnow web site (http://www.globsnow.info).

The GlobSnow project was 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 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.

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

Deliverable No	***Title***
D 1.4	Requirements Baseline Document (RB)
D 1.5	Ground Data Documentation (GDD)
D 1.6	Description of the Diagnostic Data Set (DDS)
D 1.7	Design Justification File (DJF)
D 1.8	Technical Specification (TS)
D 1.9	Design Justification File 2 (DJF-v2)
D 1.10	Acceptance and Test Document (ATD)
D 1.11	Design Definition File (DDF)
D 1.12	Qualification Review Report (QRR)
D 1.13	Prototype Validation and Assessment Report (PVAR)
D 2.3	Acceptance Review Report (ARR)
D 2.5	Design Justification File 3 (DJF-v3)
D 2.6	Production and Validation Report (PVR)
D 3.1	Service Evolution Report (SER)
D 3.2	Service Evolution Report 2 (SER-v2)

2 OVERVIEW OF PROJECT WORK AND RESULTS

2.1 Snow Extent

The GlobSnow project has developed a set of Snow Extent (SE) products covering the Northern Hemisphere based on the available time series of ERS-2 ATSR-2 and Envisat AATSR images from 1995 until present. The product time series is updated in near real time and can be freely downloaded via web or FTP. There are four product types:

- **Daily Fractional Snow Cover** (DFSC), snow fraction (%) per grid cell for all satellite overpasses on a given day
- **Daily 4-class 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 the aggregation of daily products. Available for each day based on a 7-day sliding time window giving the most recent observations highest weighting
- **Monthly Aggregated Fractional Snow Cover** (MFSC) for all satellite overpasses within a calendar month, providing the average, standard deviation, minimum and maximum FSC for the period

2.1.1 Product description

The SE products are available in a geographical (latitude/longitude) coordinate system based on the reference ellipsoid and datum WGS84, with a grid resolution of 0.01 degrees × 0.01 degrees. The products cover the Northern Hemisphere from 25°N to 84°N, which corresponds to the seasonally snow covered land areas of the Northern Hemisphere.

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. The next layers depend on the product type.

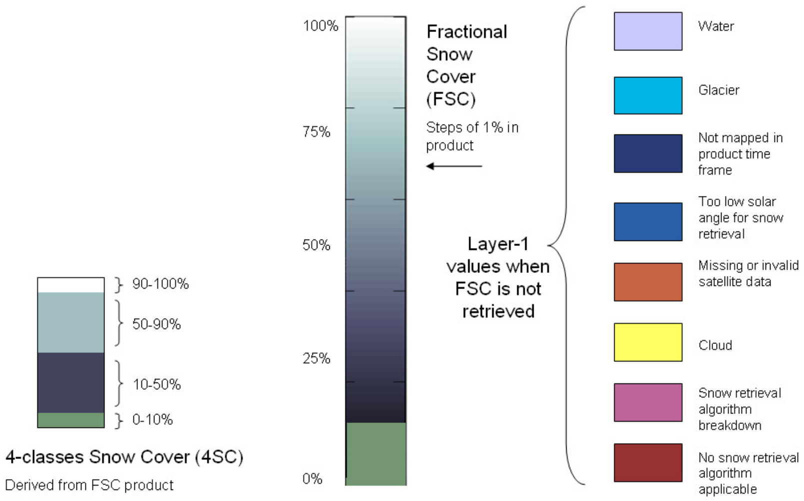

Figure 2.1: Colour legend for Layer 1 (thematic layer) of the SE products

The Daily Fractional Snow Cover (DFSC) product provides the fractional snow cover (FSC) in percentage (%) per grid cell for all satellite overpasses on a given day (Figure 2.2). The product represents the best estimate of snow cover for a single day, given the sensor capabilities. The product is generated for each day based on a 24 hour time window, and is limited by scene illumination and cloud cover.

Figure 2.2: Example of Daily Fractional Snow Cover product for 10 April 2003

The Daily 4-class Snow Cover (D4SC) product provides snow cover classified into four categories per grid cell for all satellite overpasses on a given day. The product is derived from the DFSC product and has, therefore, the same general characteristics.

The Weekly Aggregated Fractional Snow Cover (WFSC) product is based on all satellite overpasses within a seven-day period (Figure 2.3). It is generated daily, based on the DFSC products within a sliding 7-day time window including the previous six days.

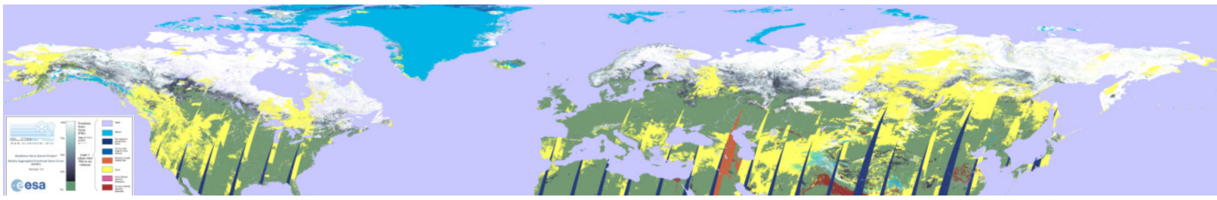

Figure 2.3: Example of Weekly Aggregated Fractional Snow Cover product for 19 April 2003

The Monthly Aggregated Fractional Snow Cover (MFSC) product is based on all satellite overpasses within a calendar month (Figure 2.4). The product provides statistics for cloud-free observations of FSC within the period. It is based on the DFSC products for the given calendar month. The product is generated and made available at the end of each month.

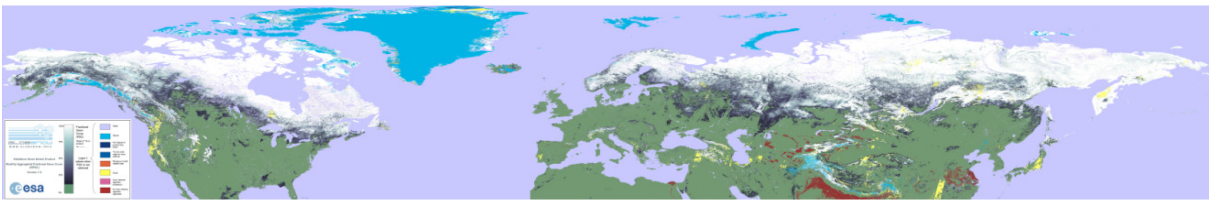

Figure 2.4: Example of Monthly Aggregated Fractional Snow Cover product for April 2003

The products are delivered in the netCDF CF 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.

2.1.2 Algorithms and processing system

The GlobSnow SE processing system applies optical measurements in the visual-to-thermal part of the electromagnetic spectrum. Full details on the theoretical basis and implementation of SE retrieval are provided in the Design Justification File deliverables (D-1.7, 1.9, and 2.5). Clouds are detected by a cloud-cover retrieval algorithm (SCDA, developed for GlobSnow purposes) and masked out. Large water bodies (oceans, lakes and rivers) and glaciers are also masked out. The snow cover information is retrieved by two algorithms, one for high-mountain areas of steep topography above the tree line (NLR) (Solberg et al. 2006) and another for forested and open areas (SCAmod) (Metsämäki et al. 2005). The domains of the algorithms are determined by the thematic masks, and the retrieval results are merged. The resulting snow cover map is the basis of the generation of the four products described previously.

2.1.3 Algorithm and product development, evaluation and validation

Project Phase 1 started by evaluating candidate algorithms for the SE product. Three well-known test sites were selected, located in Norway (high-mountain terrain, not alpine), the Alps (alpine terrain) and Finland (mixed boreal forest with some open areas). All candidate algorithms were tested with AATSR and MODIS data for days matching, or close to the available snow reference data, which included on high-resolution optical earth observation data for open areas, point measurements (weather stations), and transects (snow courses) in the boreal forest. A full description of the reference datasets used for algorithm evaluation are provided in the Ground Data Documentation deliverable (D-1.5). The algorithms chosen were the SCAmod algorithm (Metsämäki et al., 2005; Metsämäki et al., 2011) for forested and open non-alpine terrain, and the Norwegian Linear Reflectance (NLR) fractional snow cover algorithm for mountainous terrain. The algorithms were then implemented in a laboratory system for snow mapping of the pan-European region and evaluated again against other data for this larger geographical region.

During Phase 2 of the project, the laboratory system was scaled up to cover the Northern Hemisphere. Much of the algorithm improvement effort was devoted to the generation (expansion from regional scale to hemispherical scale) of the forest transmissivity map required by the SCAmod algorithm (Metsämäki et al., 2005). This was achieved through a statistical analysis between GlobCover land cover data and regional transmissivity maps for selected training areas (generated from MODIS reflectances acquired under full snow-cover conditions as described in Metsämäki et al., 2011). The SCDA-based cloud mask was evaluated visually against colour composite AATSR images for selected sites in the pan-European area. The evaluation results revealed that SCDA provides a reasonable cloud mask for most ground surfaces. The snow information in the SE product was evaluated against NSIDC MODIS FSC maps and Landsat imagery. SE mapping for the northern hemisphere was successful, and demonstrated that daily maps of FSC can be produced at this scale. The correspondence between GlobSnow products and NSIDC MODIS snow maps as well as snow maps derived from Landsat was reported in the Design Justification File deliverables. The combination of the two algorithms for mountains and flat terrain showed some discrepancies along regions where the two algorithms join. This was mitigated in Phase 3 of the project together with the implementation of improved input data quality checking, and fixes to various product anomalies. The algorithm discrepancies also led to a feasibility study where the performance of SCAmod in mountainous areas was evaluated. Preliminary results indicated that in general, SCAmod may result in similar, or even better accuracy that NLR, but further investigation is required. The latest product release covering the full time series is Version 1.2.

2.1.4 The snow extent team

The algorithms, processing chains and products have been developed jointly by NR, SYKE, ENVEO, FMI and GAMMA. NR coordinated the SE development, developed the laboratory processing chain, and was responsible for the NLR algorithm. SYKE developed the SCDA and SCAmod algorithms, while ENVEO evaluated the performance of the algorithms and collaborated in product improvements. GAMMA implemented the operational processing system. 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.

2.2 Snow Water Equivalent

The GlobSnow project has 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 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.

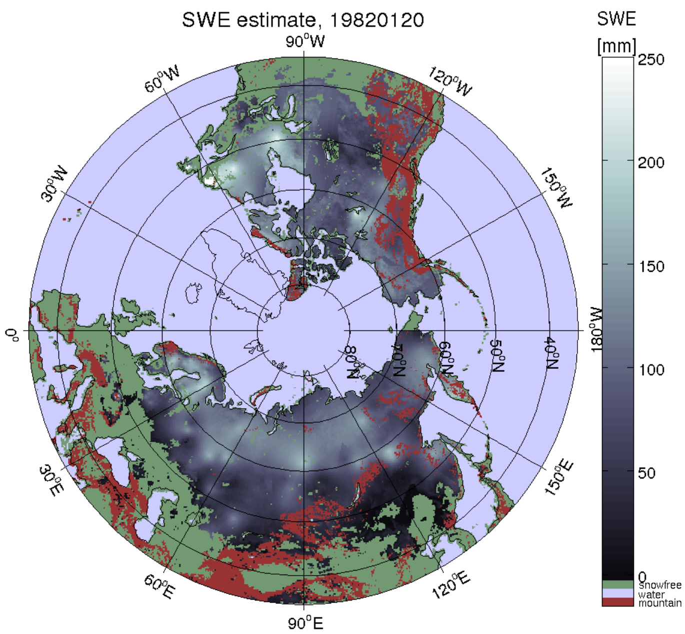

Figure 2.2.1: Example of a daily SWE product for 20 January 1982

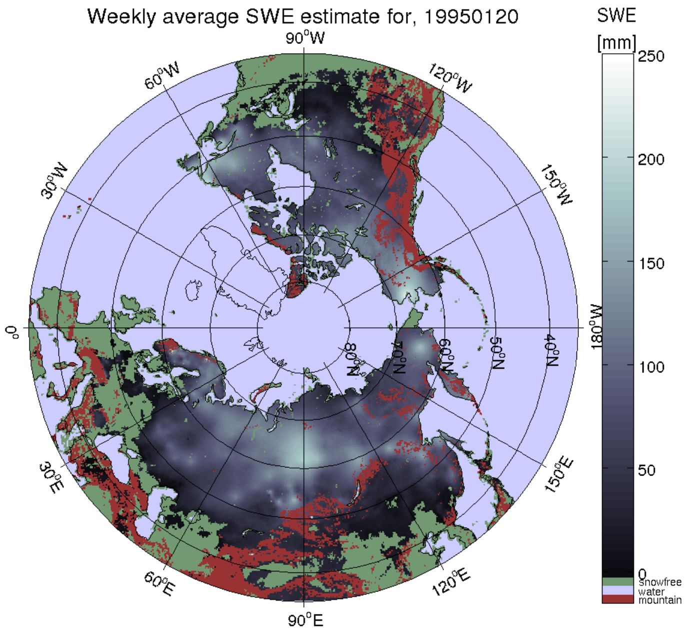

Figure 2.2.2: Example of a weekly aggregated SWE product for 20 January 1995

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, SWE values of:

- 0 mm denotes snow-free areas (Snow Extent 0%)
- 0.001 mm denote areas with melting snow (Snow Extent between 0% and 100%)
- > 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 project and presented in detail in Takala et al. (2011). The methodology produces snow water equivalent maps incorporated with information on the extent of snow cover at a coarse resolution (25 x 25km 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), 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 SWE production system was implemented on the FMI operated Cray XT5m super computer environment for production of the 30-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, reported within the Design Justification File deliverable (D-1.7), were carried out using the prototype product v.0.9 for the years 1994 through 1997, and 2005 through 2007. The assessment was carried out using independent reference data from primarily the Russian portion of northern Eurasia, Finland, and Canada. As described in the Ground Data Documentation (deliverable D-1.5), the reference data include an extensive set of snow course observations of SWE, field measurements from various research campaigns, and a gridded global SWE dataset produced at the Canadian Meteorological Centre. The evaluations carried out within the first phase of the project and reported in D-1.7 were later complemented with an assessment of SWE prototype data v.0.9.2 covering years 1992 through 2000 and 2005 through 2007 (reported in D-1.9) and during Phase 3 for the final product set v1.0 for years 1979 until 2000, reported within the Production and Validation Report v1 (D-2.6). Validation activities conducted with the Full Product Set (V1.0) are briefly summarized here.

The successful production of the final long-term dataset v1.0 starting from the fall 1979 through 2010 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 2000 allowed for an evaluation of the SWE algorithm performance over twenty consecutive years.

The reference dataset contains snow course measurements collected across the former Soviet Union and Russia extending from 1978 until 2000. 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 424,600 samples. 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 evaluations carried out for the GlobSnow SWE FPS (Full Product Set) v.1.0 utilized the weekly aggregate SWE product compared with the Russian snow course data. The results show an extremely 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 1979–2000, consisting of 121,584 samples) was 31.9 mm. The bias for the same dataset was +4.2 mm. Consideration of all the samples of the full dataset (all

SWE values, consisting of 137,379 samples) showed a bias of -4.8 mm and RMS error of 44.9 mm (both values are a significant improvement over the alternative evaluated algorithms; as described in full in 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 during earlier evaluations (reported in deliverables D-1.7, D-1.9, and D-2.5) 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, and planning for the production of the data 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.

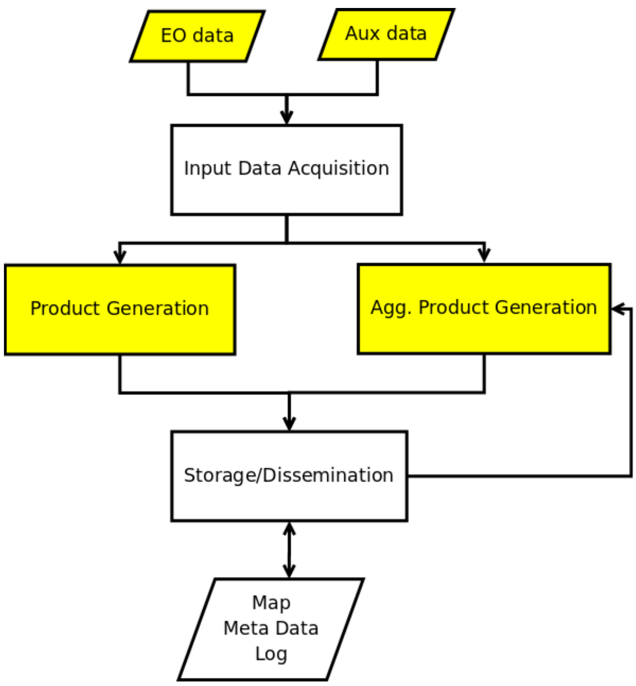

Figure 2.3.1: Generalized processing chain architecture.

The GlobSnow products are provided in netCDF format that follows the CF (Climate and Forecast) version 1.0 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 products 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.

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	SMMR / SSMI Synoptical weather data
Auxilary data	Mountain mask Water mask Forest mask Glacier mask Transmissivity mask	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	3-4 hours	30 min
Projection	Lat/Lon WGS 84	EASE-Grid North
Pixel spacing	0.01 deg. x 0.01 deg.	25 km x 25 km

3 CONCLUSIONS

3.1 Snow Extent

The Snow Extent (SE) Full Product Set (FPS) Version 1.2 for the Northern Hemisphere contains information on snow coverage 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.

Project Phase 1 started by evaluating candidate algorithms for the SE product. Two algorithms were finally chosen, one for forested and open relatively flat terrain and one for mountainous terrain. The algorithms were then implemented in a laboratory system for snow mapping at the pan-European level and evaluated against other data for this larger geographical region. The laboratory system was then, in Phase 2, scaled up to cover the Northern Hemisphere. Some algorithm improvements were included in this version. Subsequent evaluation revealed that the cloud detection algorithm provides a reasonable cloud mask for most ground surfaces and cloud types. The snow information in the SE product was evaluated against MODIS snow products and Landsat data. SE mapping at the northern hemispheric coverage was successful and demonstrated that maps of FSC can be retrieved at this scale. Some FSC misinterpretations due to unrecognized clouds could be mitigated through advanced decision-based filtering techniques. In Phase 3, further improvements were implemented resulting in better product quality and flagging of incomplete input data. The latest product release covering the full time series is Version 1.2.

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 datasets. The GlobSnow SE dataset complements the previous records generated with greater temporal extent 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 enhancing our understanding of historical snow conditions.

3.2 Snow Water Equivalent

The GlobSnow Snow Water Equivalent (SWE) product set version 1.2 for the Northern Hemisphere provides information on SWE retrieved from SMMR and SSM/I passive microwave sensors, combined with ground-based weather station data, from 1979 until 2011. It is the first satellite-based daily SWE dataset at a hemispheric scale for 30+ years. Based on the extensive validation efforts conducted within the GlobSnow project, the product shows a consistent performance over the whole 30+ years of record, and represents a noted improvement over other existing SWE products.

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. By combining the information available from the weather station observations with forward snow emission model simulations, the GlobSnow SWE algorithm performs better under deep snow and wet snow conditions than any pre-existing method. The GlobSnow methodology also provides a grid cell by grid cell uncertainty estimate for each SWE retrieval as a product of the assimilation scheme. The SWE production system v1.2 utilizes the SWE retrieval methodology refined within the GlobSnow project and presented in Takala et al. (2011).

According to the assessment of the SWE product, the algorithm developed within the GlobSnow project meets and in several aspects exceeds the criteria from the original ESA statement of the work for the project. The evaluations carried out for the SWE FPS v1.0 and v1.2 products, reported within the project deliverables show that the retrieval accuracy is higher than achieved by the alternative existing state-of-the-art algorithms, due largely to improved sensitivity to deep snow (SWE between 100 and 150 mm); by utilizing the information available from the weather station observations it enables an increased temporal and spatial coverage when compared with the other algorithms, and it provides an uncertainty estimate for the retrieved SWE estimates on a grid cell level. In addition, the performance of the algorithm is very consistent on a year-to-year basis, as examined by the SWE development team for the time span between 1979 and 2009. The findings of the SWE development efforts are reported in full detail within the project deliverables: DJF-v1, DJF-v2, DJF-v3, PVR-v1 and SER.

The SWE FPS v1.2 product spans the Northern Hemisphere for years 1979 to 2011. 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 variances (error estimates) is provided with the dataset. The data are available through both the LitDB FTP server and a web-based data dissemination site.

4 RECOMMENDATIONS

4.1 Snow Extent

Recommendations for the future Snow Extent development efforts are:

- Generate a bare-ground reflectance map representing conditions just after the snow season (with senescent vegetation) for the reduction of SE product uncertainty for sparsely forested, open and mountainous regions. This must be based on an assimilation of several years of reflectance observations in order to remove the effects of clouds in the pixels and other uncertainty issues. The reflectance values can be generated pixel-wise or for certain land-cover classes; both approaches should be tested.

- Extend the uncertainty model work to cover the largest possible non-mountainous areas for model calibration, then continue the development of a similar model for mountainous regions which also takes into account the effects from the terrain relief and solar elevation. The two models could then be combined into a complete SE product uncertainty model for the generation of a pixel-wise uncertainty estimates.

- Topographic correction of reflectance values is especially important for snow mapping in mountain regions, so it is necessary to investigate methods for reducing topographic effects on the reflectance values at the global scale. Topographic correction is especially important for single-channel snow algorithms.

- SE algorithm improvements:

    - Work towards a well-justified selection of the algorithm for mountainous areas requires additional effort. If two separate algorithms (one for mountains, the other for non-alpine areas) for GlobSnow SE are preferred, a method for combining these algorithms smoothly and consistently in the transition zone should be developed.

    - Study and demonstrate the capabilities of a multi-spectral algorithm, (which makes use of the bands in the VIS, NIR and SWIR; e.g. 4 bands AATSR, 8 bands MODIS) for fractional snow mapping on global scale. Topographically corrected reflectance values at the various bands should be used as input to the algorithm.

    - Work towards a still improved performance on capturing snow in dense forests. Snow in dense forest is typically a challenge for remote sensing methodologies; however, some improvement could be achieved.

- Improve the generation of weekly and monthly aggregates. Undetected cloudy areas outside the snow season are in most cases falsely classified as snow covered. This is particularly a problem with weekly and monthly aggregates if the value is based on a single erroneous observation. In order to avoid these artifacts, extra decision rules are needed. These rules would have to reflect the climatologically "normal" snow conditions of the geographical area in concern, as well as filtering the data sequence if several values within aggregation period are available.

- The inter-comparison of GlobSnow SE V1 product with MODIS snow products enabled the detection major misclassifications on a global scale. In the next step, the inter-comparison with snow maps from high-resolution data (as it has been already demonstrated for a limited Landsat TM data set) should be extended to different regions, environments, and seasons. This will also enable a better specification of the product quality.

4.2 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. Currently, sub-grid land cover fractions are not accurately considered in the SWE retrieval system, even though the relative contributions of lakes, forests, wetlands, and clearings can have a major influence on microwave emission. Consideration of lake and wetland fraction would make the retrieval system more physically sound. In addition, the GlobSnow V1.2 FPS utilized a fixed snow density (0.24 g/cm^3) regardless of location and season. An immediate improvement could be realized by implementing a varying snow density by employing the climatological snow classes as defined by Sturm et al. (1995).

b. Supplementary products in addition to the current SWE and SWE variance fields could be developed. Possibilities include a SWE field that excludes the background snow depth interpolated from synoptic stations (i.e. radiometer-only retrieval which is relevant e.g. for the integration to NWP systems) and a wet snow cover/dry snow cover field. Another additional product would be the improved effective snow grain size. The use of the improved snow emission modeling enables the production of physically reasonable snow grain size information.

c. Both (a) and (b) require the revision of algorithm into a more unified modular code that also facilitates the integration of sub-programs to assimilation systems (NWP) and to other near-real-time applications.

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. The work would also benefit the development of new satellite missions including the planned CoReH2O Earth Explorer of ESA. The SWE mapping with CoReH2O SAR could utilize the GlobSnow-based SWE or effective snow grain size information as an initial background field for the high-resolution SWE mapping.

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 (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 surface snow observing sites 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. 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.

- Analysis of coincident snow surveys and point climate station measurements of snow depth have shown that land cover has a controlling influence on the uncertainty in surface snow depth measurements. The current GlobSnow SWE algorithm assigns a fixed variance to all climate station measurements regardless of land cover. Assigning variance based on land cover would address this shortcoming.

- The possibility of including SWE estimates for mountainous regions needs to be investigated. The common understanding is that the coarse resolution radiometer data are not suitable for SWE retrievals in mountainous regions due to complex sub-grid heterogeneity in terrain, land cover, and snow distribution. However, the potential of the GlobSnow methodology, where radiometer data and ground-based weather station data are utilized in an assimilation scheme, has not yet been extensively evaluated over mountainous regions.

- 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) could be used for validation.

- 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 need 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.

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