Global Snow Monitoring for Climate Research

Snow Water Equivalent (SWE) product guide

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

PREPARED BY

KARI LUOJUS, Jouni PULLIAINEN, MATIAS TAKALA and JUHA LEMMETYINEN (FMI); Chris DERKSEN AND LIBO WANG (EC)

GLOBSNOW CONSORTIUM

Finnish Meteorological institute (FMI) - Prime contractor

ENVEO IT GmbH (ENVEO)

Environment Canada (EC)

Finnish Environment Institute (SYKE)

GAMMA Remote Sensing Research and Consulting AG (GAMMA)

Norwegian Computing Center (NR)

ESA TECHNICAL OFFICER: Bojan BOJKOV

DATE: 15 December 2010

VERSION / REVISION: 1.0 / 01

Table of Contents

1 OVERVIEW OF THE GLOBSNOW SWE PRODUCT

Disclaimer:
The GlobSnow SWE product is derived using a combination of ground based data and satellite microwave radiometer-based measurements. Due to the nature of the radiometer observations, the SWE product is reliably shown on areas with seasonal dry snow cover. Areas with sporadic wet snow or a thin snow layer are not reliably detected and typically not present on the SWE product. The areas marked as snow free may thus include areas with occasional wet snow cover.

The European Space Agency (ESA) Data User Element (DUE) GlobSnow Snow Water Equivalent (SWE) product set version 1.0 for the Northern Hemisphere represents information on snow water equivalent retrieved from SMMR, SSM/I, and AMSR-E sensors combined with ground-based weather station data from 1979 until present. In addition to the satellite data ECMWF collected weather station observations are employed. The SWE products are saved in both NetCDF CF and HDF4-formats: a single file contains the data for a single day; and a single file contains two fields 1) the SWE estimate and 2) an error estimate. *The snow water equivalent describes the amount of liquid water in the snow pack that would be formed if the snow pack was completely melted.*

The SWE product is produced by the GlobSnow consortium. The main responsibility for the production of SWE data lay with Finnish Meteorological Institute (FMI) and Environment Canada (EC). Additional assistance for the production of the data has been given by ENVEO IT GmbH (ENVEO), Finnish Environment Institute (SYKE), GAMMA Remote Sensing AG (GAMMA), Norwegian Computing Center (NR) and Northern Research Institute (Norut).

The SWE production system v1.0 utilizes SWE retrieval methodology (Pulliainen 2006) complemented with a time-series melt-detection algorithm (Takala et al. 2009). The two algorithms are combined to produce snow water equivalent maps incorporated with information on the extent of snow cover on coarse resolution (25 x 25km grid cells). The SWE estimates are complemented with uncertainty information on a grid cell level.

The GlobSnow SWE processing system applies passive microwave observations 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 and Greenland. A semi-empirical snow emission model is used for interpreting the passive microwave (radiometer) observations through model inversion to the corresponding SWE estimates.

The basis of the SWE processing system is presented in an article by Pulliainen (2006). As applied for GlobSnow, estimates of SD (snow depth) based on emission model inversion of two frequencies, 18.7 and 36.5 GHz, are first calibrated over EASE grid cells with weather station measurements of SD available. Snow grain size is used in the model as a scalable model input parameter (being determined from the input radiometer and weather station data). These values of grain size are used to construct a Kriging interpolated background map of the effective grain size, including an estimate of the effective grain size error. The map is then used as an input in model inversion over the span of available radiometer observations, providing an estimate of SD. In the inversion process, the effective grain size in each grid cell is weighed with its respective error estimate. A snow density value is applied to each grid cell to connect depth to SWE. Areas of wet snow are masked according to observed brightness temperature values using an empirical equation, as model inversion of SD/SWE over areas of wet snow is not feasible due to the saturated brightness temperature response. The weather station observations of SD are further interpolated to provide a crude estimate of the SD (or SWE) background. The SWE estimate map and SD map from weather station observations are combined using a Bayesian spatial assimilation approach to provide the final SWE estimates.

The snow emission model applied is the semi-empirical HUT snow emission model (Pulliainen et al., 1999). The model calculates the brightness temperature from a single layer homogenous snowpack covering frozen ground in the frequency range of 11 to 94 GHz. Input parameters of the model include snowpack depth, density, effective grain size, snow volumetric moisture and temperature. Separate modules account for ground emission and the effect of vegetation and atmosphere. The model has been validated against tower-based and airborne reference radiometer observations (see e.g. Pulliainen et al., 1999, Lemmetyinen et al., 2009).

The detection of snow extent is based on a time-series melt detection approach described in (Takala et al. 2009). The algorithm can be used to determine the onset of snow-melt season using the available radiometer observations on a hemispherical scale covering the GlobSnow SWE time-series up to present day. The methodology has been calibrated against a vast Pan-Arctic dataset covering most of the land-areas of Northern Eurasia between the years 1979 to 2001. The areas that are identified as snow covered within the melt detection algorithm but for which a SWE estimate is not produced are given a marginal SWE value (0.001 mm) in the final SWE product. This information can be used to determine the extent of snow cover. The areas with a SWE value of 0mm are bare ground and areas with SWE of 0.001 mm or above are snow covered.

The SWE data is provided NetCDF CF-format and HDF-format. In addition to the raw SWE data, quicklook images are generated in png-format.

2 DESCRIPTION OF THE PRODUCT

The SWE product is projected to Equal-Area Scalable Earth Grid (EASE-Grid) and provides the whole Northern Hemisphere (lambert's equal-area azimuthal – projection) in a single data field. The nominal resolution of single pixel is 25 km x 25 km and the geometry of the pixels varies. The data field has the size of 721 x 721 (rows x columns). Although the EASE-Grid can represent data almost to the equator the product is limited between latitudes 35° and 85° for physical reasons.

There are three products (all in the EASE-Grid) derived for SWE:

- **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.

In addition to the information on snow water equivalent, the SWE product includes 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 denote snow-free areas (Snow Extent 0%)
- 0.001 mm denote areas with melting snow (Snow Extent between 0% - 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 0.001mm. The areas that are determined as snow-free or melted by the melt detection approach are denoted with a SWE value of 0mm. All the other areas show a retrieved SWE value (that is in all cases greater than 0.001mm).

The weekly (7-days) 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 SWE (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.

The input data for the SWE products are SMMR for 1979-1987, SSM/I for 1987-2002 and AMSR-E for 2003–2009 all acquired from NSIDC (AMSRE 2004) in EASE-Grid projection with a nominal spatial resolution of 25 km.

The weather station synoptic data is acquired from The European Centre for Medium-Range Weather Forecasts (ECMWF). The weather station data applied for the production of the SWE data contain the measured snow depth at the station locations.

The SWE product file includes two data fields:

- The SWE estimate [mm]
- The variance of the SWE estimates [mm] (i.e. the accuracy information for each SWE sample).

The data type of both data fields is a 32 bit floating point ‘float 32’. Positive values and zero are reserved for SWE and negative values for flags. The physical values of SWE are in millimeters. Negative values mean that the pixel is masked out due to water, mountains or no data (value of -1 is used for water bodies and -2 for mountains).

The mountainous areas of Northern Hemisphere are masked out from the SWE product. The mountain mask applied is derived from 4 minute averaged ETOPO2 data set which includes the Global elevation and bathymetry on 2x2 minute grid from the National Geophysical Data Center (NGDC). The dataset was original published in September 2001 and was revised to include correction to Caspian Sea area in April 2006. It contains improvements that include the blending of satellite altimetry with ocean soundings and new land elevation data from the Global Land One-km Base Elevations (GLOBE) project.

SWE estimates for wet snow areas (where retrieval using the radiometer data is not feasible) are determined from the weather station data using kriging interpolation. The methodology used to derive the snow line is described in (Takala et al. 2009).

The land-mask and the forest masks utilized are derived from the European Commission, Joint Research Centre, Global Land Cover 2000 database (GLC 2000) -data. The GLC2000 data were regridded and resampled for the EASE-Grid 25 km resolution by FMI.

2.1 Naming convention

The SWE products are named according to the following convention:
Globsnow_SWE_<type>_<datestring>_<versionstring>.<extension>
Where:
<type> is “L3A“ for the daily data; “L3B“ for aggregated products (weekly/monthly)
<datestring> is the date in “yyyymmdd“ -notation
<versionstring> is the product version (1.0 is the current data version)
<extension> is either “nc” or “hdf” – referring to NetCDF CF or HDF4

For example: "GlobSnow_SWE_L3A_20030131_v1.0.nc" is the daily SWE data for January 31st 2003, product version 1.0 in NetCDF CF format.

The metadata fields included within the HDF4 and NetCDF CF-files contain general information on the products.

3 PRELIMINARY VALIDATION RESULTS

The GlobSnow SWE product is generated using the FMI algorithm (Pulliainen 2006). The selection of this algorithm for the GlobSnow SWE product was the result of extensive evaluation of several different algorithms for three distinct test sites/regions over three winter seasons. The evaluated algorithms included the FMI algorithm (Pulliainen 2006), Chang algorithm (Chang et al. 1987), EC algorithms (Derksen et al., 2003; Derksen 2008; Derksen et al, in review), SPD algorithm (Asbacher 1989) the NSIDC operational algorithm (Armstrong et al. 2001), and the AMSR-E standard SWE product (Kelly et al., 2003). The test sites were: 1) Northern Eurasia, including data from the years 1995 to 1997 2) Finland containing ground truth data from the years 2005 to 2008 and 3) central Canada including data from the years 2005 to 2008. The complete algorithm evaluation, including an overview of the algorithms, reference datasets, and results is presented in the GlobSnow Design Justification File (Solberg et al., 2009) available via the GlobSnow website (globsnow.fmi.fi).

Eurasia

Table 1 shows the results acquired for a large dataset of more than 20 000 samples. The FMI approach was more accurate than that of the other algorithms/approaches. The results were acquired using SSM/I based satellite data-derived SWE estimates in comparison with ground truth snow depth measurements conducted from Russian snow course measurement (INTAS-SCCONE snow course measurements).

Table 1. Summary of tested SWE algorithms over test area Eurasia, full dataset of Jan. 1995- Dec. 1997.

Name	***RMSE***	*bias*	*Corr. coeff*	*Unbiased RMSE*	*Samples*
FMI algorithm	43.2 mm	-3.1 mm	0.611	43.1 mm	26063
EC algorithm	67.6 mm	-28.2 mm	0.210	61.5 mm	18109
Chang et al. 1987 (asc node) Chang et al. 1987 (desc node)	71.6 mm 70.7 mm	-8.4 mm 1.6 mm	0.011 0.029	71.1 mm 70.8 mm	26726 27521
SPD algorithm (asc node) SPD algorithm (desc node)	67.1 mm 63.9 mm	-12.7 mm -3.1 mm	0.052 0.121	65.9 mm 63.9 mm	29559 29451
Armstrong et al. 2001 (asc node) Armstrong et al. 2001 (desc node)	72.3 mm 73.7 mm	-44.1 mm -42.9 mm	0.044 0.029	57.3 mm 59.9 mm	21796 24791

It is evident from Table 1 that the Chang algorithm (and the two derivates investigated) had large RMS errors against the validation data, while the SPD algorithm performed slightly better than the EC algorithm suite in this respect. The relatively weak performance of the EC algorithm suite was expected, as it was developed originally for Canadian land cover and snowpack characteristics, and appears to be hampered by the lack of direct 10 GHz measurements from SSM/I that are utilized to retrieve SWE from AMSR-E measurements under deep snow conditions across the boreal forest (Derksen, 2008). In terms of bias, both the original Chang algorithm and the SPD algorithm perform relatively well when using data from SSM/I descending orbits. The overall bias value is misleading however, as a slight overestimation for shallow snow is compensated by a very large underestimation of areas with high SWE.

The FMI algorithm shows RMSE of 43.2 mm for Eurasia with the complete dataset (26063 samples). Restricting the analysis to SWE values below 150 mm, the FMI algorithm gives an RMSE of 33.5 mm (23889 samples). Other algorithms show RMS errors well beyond this. An illustration of the northern Eurasian test region is shown in Figure 1. An illustration of the SWE estimation accuracy for different SWE intervals acquired using the selected GlobSnow algorithm is shown in Figure 2.

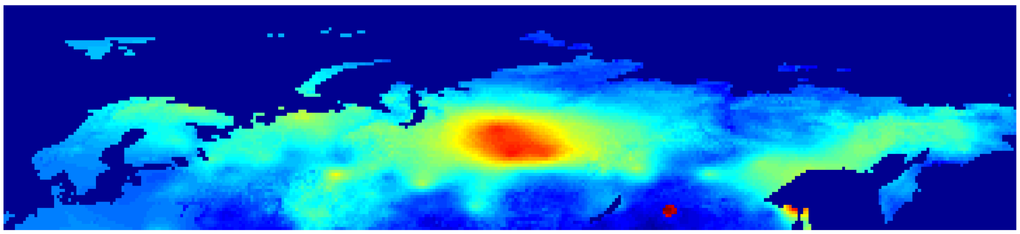

Figure 1. T*he utilized test site: North Eurasia, illustrated with SWE estimates acquired from the FMI algorithm for 10 January 1996.*

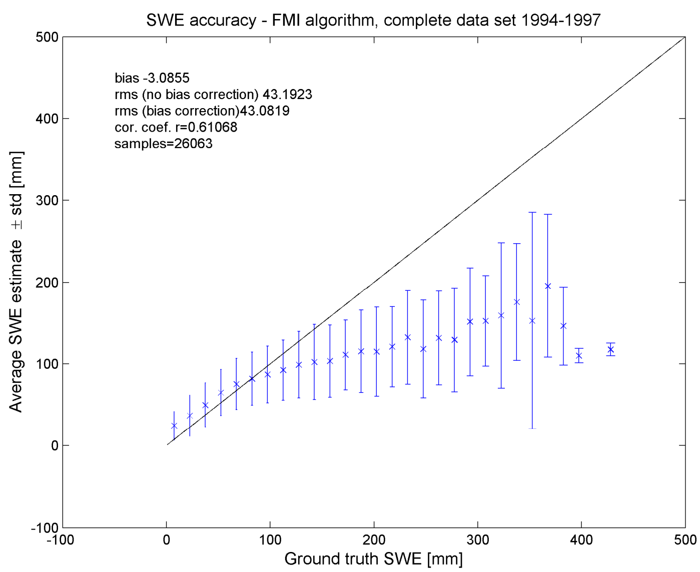

Figure 2. A visualization *of the SWE estimation algorithm performance over Eurasia.*

Finland

Three algorithms were evaluated over Finland: the Environment Canada algorithm suite, the NASA AMSR-E/Aqua L3 Northern Hemisphere SWE product (www.nsidc.org/data/ae_dysno.html), and the FMI algorithm. Input brightness temperatures were from AMSR-E for the 2005/06 through 2007/08 winter seasons. Finnish snow course measurements were used for validation, and are made ideally on the 15th of each month, but in practice the measurement dates range from the 12th to the 18th.

A summary of the evaluation results are in Table 2 and Figure 3. For the entire three-year dataset, the FMI algorithm had an RMSE of 34.4 mm, thus being within the target accuracy of RMSE < 40 mm as determined in the GlobSnow research baseline. The strong performance of the FMI algorithm was expected, as the FMI algorithm benefits from a large number of weather station inputs (ca. 40 WMO stations) available. Moreover, detailed vegetation cover information (forest biomass) from a national database was used. Uncertainty of EC algorithm suite was lower than the standard AMSR-E product, although for SWE values above 120 mm, sensitivity to increasing SWE was low.

Table 2. Summary of tested SWE algorithms over Finland, winter periods 2005-2008.

Name	***RMSE (mm)***	***Bias (mm)***	***Corr. coeff***	***Unb. RMSE (mm)***	***Samples***
AMSR-E/Aqua 5-Day L3 Global Snow Water Equivalent	57.5	-28.0	0.17	47.4	1189
EC algorithm (5-day average)	43.1	-14.0	0.62	41.1	1256
FMI algorithm (5-day average)	29.8	8.0	0.84	28.7	1191

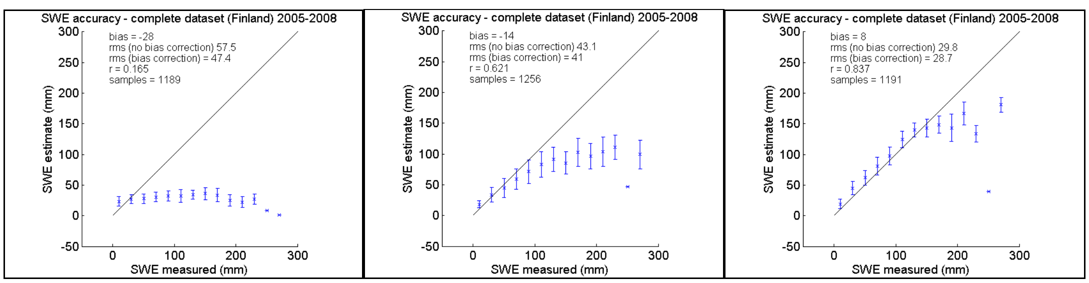

Figure 3. *algorithm performance over Finland versus national snow course observations, for the NASA AMSR-E SWE product (left), EC algorithm suite (centre) and FMI algorithm (right).*

Canada

Three algorithms were evaluated over regions of Canada: the Environment Canada algorithm suite, the NASA AMSR-E/Aqua L3 Northern Hemisphere SWE product (www.nsidc.org/data/ae_dysno.html), and the FMI algorithm. Input brightness temperatures were from AMSR-E for the 2005/06 through 2007/08 winter seasons. Reference datasets included field observations from various scientific campaigns, hourly automated snow depth observations from the Boreal Ecosystem Monitoring Sites (BERMS), Environment Canada snow courses, and daily global gridded SWE data produced operationally at the Canadian Meteorological Centre (see Brasnett, 1999).

A summary of algorithm validation results relative to ground measurements and separated by land cover is shown in Table 3. A summary of validation results with the CMC analysis is shown in Table 4. In general, the NASA algorithm had the highest uncertainty relative to ground measurements, particularly in tundra environments, and exhibited the weakest agreement with the CMC product. In comparison with ground datasets, the EC algorithms performed particularly well in tundra and northern boreal environments. Disagreement with the CMC gridded product, however, was evident in northern environments, the source of which may actually be uncertainty in the CMC analysis itself. The FMI algorithm exhibited consistently strong performance relative to field observations and the CMC analysis for all land cover types.

Table 3. Summary of algorithm validation for Canadian regions, separated by land cover (all years considered).

RMSE (mm)	**EC**	**NASA**	**FMI**
Tundra	20	65	50
Northern Boreal	50	74	77
Southern Boreal	32	33	24
BERMS	32	28	24
Prairie	21	37	32

Mean Bias (mm)	**EC**	**NASA**	**FMI**
Tundra	-10	-84	-9
Northern Boreal	-23	-36	-48
Southern Boreal	-16	-6	-10
BERMS	-8	-1	-1
Prairie	1	26	7

Correlation (r)	**EC**	**NASA**	**FMI**
Tundra	0.83	0.52	0.91
Northern Boreal	0.71	0.00	0.24
Southern Boreal	0.61	0.63	0.70
BERMS	0.72	0.82	0.84
Prairie	0.59	0.41	0.23

Table 4. Summary of validation results: SWE retrievals versus CMC gridded SWE.

RMSE			
2006	**EC**	**NASA**	**FMI**
Pentad 1	25.7	28.0	19.6
Pentad 7	34.8	38.6	21.1
Pentad 13	42.9	42.7	27.6
Pentad 19	55.4	90.7	25.8
2007	**EC**	**NASA**	**FMI**
Pentad 1	29.8	36.2	23.9
Pentad 7	40.0	41.4	26.2
Pentad 13	51.6	45.9	39.0
Pentad 19	77.7	72.5	36.4
2008	**EC**	**NASA**	**FMI**
Pentad 1	25.9	29.3	26.6
Pentad 7	40.1	45.2	25.4
Pentad 13	45.0	49.2	35.5
Pentad 19	53.7	65.4	36.0

Correlation (r)			
2006	**EC**	**NASA**	**FMI**
Pentad 1	0.36	0.11	0.89
Pentad 7	0.31	0.17	0.76
Pentad 13	0.13	0.13	0.75
Pentad 19	0.41	0.08	0.73
2007	**EC**	**NASA**	**FMI**
Pentad 1	0.14	-0.01	0.57
Pentad 7	0.27	0.13	0.63
Pentad 13	0.13	0.19	0.47
Pentad 19	0.39	0.13	0.73
2008	**EC**	**NASA**	**FMI**
Pentad 1	0.33	0.30	0.66
Pentad 7	0.26	0.23	0.68
Pentad 13	0.26	0.14	0.65
Pentad 19	0.44	0.13	0.69

As noted in the results for Eurasia, passive microwave SWE retrieval algorithms have a well documented tendency to systematically underestimate SWE under deep snow conditions due to a change in the microwave behaviour of the snowpack (when SWE exceeds approximately 150 mm, the snowpack transitions from scattering a scattering medium to a source of emission). The highest RMSE and bias values, and lowest correlations for all algorithms were over the boreal forest, the only Canadian region under investigation for which SWE regularly exceeds the 150 mm threshold. To determine the impact of deep snow on algorithm performance, statistics were re-computed using a 150 mm threshold, and are summarized in Table 5. In general, algorithm performance improved appreciably when the deep snow cases (SWE >150 mm) were not considered.

Table 5. Impact of deep snow on SWE retrieval accuracy in the boreal forest of central Canada.

All	EC	NASA	FMI
RMSE	50	74	77
Bias	-23	-36	-48
Correlation	0.71	0.00	0.24
SWE <150	**EC**	**NASA**	**FMI**
RMSE	29	34	25
Bias	-4	-2	-17
Correlation	0.38	0.01	0.70

Conclusions based on the results presented above are: The FMI algorithm exhibited consistently strong performance for all regions and levels of validation. Some regions with a sparse climate station observing network (tundra and northern boreal forest) may require further attention, but given (1) the evaluation results, and (2) the uncertainty estimates produced from the assimilation method, the FMI algorithm most satisfactorily address the GlobSnow requirements.

3.1 Known issues with the SWE product

Availability of the early SWE data is limited due to two reasons: 1) Availability of ground-based weather station data prior the fall of 1979 2) operation of the SMMR sensor during 1978 to 1987.

Although the SMMR data set begins from late October 1978, the ECMWF collected ground-based weather station data record does not contain measurements before fall 1979. Therefore the SWE data set begins in November 1979 (as both microwave radiometer and ground-based weather station data are required to derive accurate SWE estimates).

The passive microwave data for 1979 to 1987 are acquired from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) sensor which was operating every other day and thus can be used to derive the daily SWE time-series for every second day. The weekly aggregated SWE dataset however can be (and is) calculated for every day. The Special Sensor Microwave/Imager (SSM/I) family of sensors have been flown aboard several DMSP-satellites, covering an impressive data record starting from 1987. The SSM/I data are available for every day and the daily SWE products are generated for every day starting from fall 1987.

4 DATA ACCESS AND CONTACT INFORMATION

The products are stored at a file server with the Finnish Meteorological Institute.
The data can be accessed through www-based service or via ftp:

- http://www.globsnow.info/data/ (general data-page)
- http://www.globsnow.info/swe/ (direct link to SWE data)
- ftp://litdb.fmi.fi (for FTP-access details, please contact: kari.luojus@fmi.fi)

There is one catalogue for each product version (e.g., SWE_v.1.0). There is one sub-catalogue for each year, each with the following sub-catalogues:

- L3A_daily_SWE: Daily SWE products (in NetCDF CF -format)
- L3A_daily_SWE_HDF: Daily SWE products (in HDF -format)
- L3A_daily_quicklooks: Quicklook images for the Daily SWE products

- L3B_weekly_SWE: Weekly SWE products (in NetCDF CF -format)
- L3B_weekly_SWE_HDF: Weekly SWE products (in HDF -format)
- L3B_weekly_quicklooks: Quicklook images for the weekly SWE products

- L3B_monthly_SWE: Monthly SWE products (in NetCDF CF -format)
- L3B_monthly_SWE_HDF: Monthly SWE products (in HDF -format)
- L3B_monthly_quicklooks: Quicklook images for the monthly SWE products

The quick-look pictures are provided for quick and easy browsing in Portable Network Graphics (PNG) format. They are stored in separate sub-catalogues for easy handling of multiple files. One might download a whole year of images and browse the time series conveniently by stepping ('clicking') through them all using a standard photo viewer.

4.1 Contact information

If any questions arise concerning the SWE product or the GlobSnow project, do not hesitate to contact Dr. Kari Luojus. (email: kari.luojus@fmi.fi). For any question, please include Dr. Bojan Bojkov as cc for the communications (email below).

- For information about the GlobSnow project, contact kari.luojus@fmi.fi
- For login access to the FTP server, contact kari.luojus@fmi.fi
- For technical questions about SWE products, contact matias.takala@fmi.fi
- For ESA's technical project officer, contact bojan.bojkov@esa.int

Additional information on the ESA DUE GlobSnow project and the products can be found at the web-site http://www.globsnow.info.

5 REFERENCES

Armstrong, R.L. and Brodzik, M.J., 2001. Recent northern hemisphere snow extent: A comparison of data derived from visible and optical satellite sensors. *Geophysical Research Letter*s, vol. 28, pp. 3673-3676.

Aschbacher, J. 1989. Land surface studies and atmospheric effects by satellite microwave radiometry. Ph.D. dissertation, Univ. of Innsbruck.

Brasnett, B. 1999. A global analysis of snow depth for numerical weather prediction. Journal of Applied Meteorology. 38: 726-740.

Chang, A. T. C., J. L. Foster, and Dorothy K. Hall. 1987. Nimbus-7 Derived Global Snow Cover Parameters. *Annals of Glaciology* 9: 39-44.

Data Announcement 88-MGG-02, Digital relief of the Surface of the Earth. NOAA, National Geophysical Data Center, Boulder, Colorado, 1988. (ETOPO5)

Derksen, C., P. Toose, A. Rees, L. Wang, M. English, A. Walker, and M. Sturm. In review. Development of a tundra-specific snow water equivalent retrieval algorithm for satellite passive microwave data. Remote Sensing of Environment.

Derksen, C. 2008. The contribution of AMSR-E 18.7 and 10.7 GHz measurements to improved boreal forest snow water equivalent retrievals. *Remote Sensing of Environment*. 112: 2700-2709.

Derksen, C., A. Walker, and B. Goodison. 2003. A comparison of 18 winter seasons of in situ and passive microwave derived snow water equivalent estimates in Western Canada. *Remote Sensing of Environment* 88(3): 271-282.

ETOPO2v2 Global Gridded 2-minute Database, National Geophysical Data Center, National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce, http://www.ngdc.noaa.gov/mgg/global/etopo2.html <https://owa.ec.gc.ca/exchweb/bin/redir.asp?URL=http://www.ngdc.noaa.gov/mgg/global/etopo2.html>.

Global Land Cover 2000 database. European Commission, Joint Research Centre, 2003. http://gem.jrc.ec.europa.eu/products/glc2000/glc2000.php. (GLC2000)

Kelly, R., A. Chang, L.Tsang, and J. Foster. 2003. A prototype AMSR-E global snow area and snow depth algorithm. IEEE Transactions on Geoscience and Remote Sensing. 41(2): 230-242.

Knowles, K., M. H. Savoie, R. L. Armstrong, and M. J. Brodzik. 2006. /AMSR-E/Aqua daily EASE-Grid brightness temperatures, [January 2003 – December 2008]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media. (AMSRE 2004)

Lemmetyinen, J., C. Derksen, J. Pulliainen, W. Strapp, P. Toose, A. Walker, S. Tauriainen, J. Pihlflyckt, J.-P. Kärnä, and M. T. Hallikainen. A comparison of airborne microwave brightness temperatures and snowpack properties across the boreal forests of Finland and western Canada. IEEE Transactions on Geoscience and Remote Sensing, 47: 965–978.

Pulliainen, J., J. Grandell, and M. T. Hallikainen. HUT Snow Emission Model and its Applicability to Snow Water Equivalent Retrieval. IEEE Transactions on Geoscience and Remote Sensing. 37: 1378-1390.

Pulliainen, J. “Mapping of snow water equivalent and snow depth in boreal and sub-arctic zones by assimilating space-borne microwave radiometer data and ground-based observations”. Remote Sensing of Environment. 101: 257-269.

Solberg, R., J. Amlien, H. Koren, B. Wangensteen, K. Luojus, J. Pulliainen, M. Takala, J. Lemmetyinen, T. Nagler, H. Rott, F. Muller, C. Derksen, S. Metsamaki, and K. Bottcher. 2009. Global Snow Monitoring for Climate Research - Design Justification File. European Space Agency Study Contract Report 21703/08/I-EC Deliverable 1.7. 246 pages.

Takala, M., Pulliainen, J., Metsämäki, S. and Koskinen, J. 2009 Detection of Snowmelt Using Spaceborne Microwave Radiometer Data in Eurasia From 1979 to 2007. IEEE Transactions on Geoscience and Remote Sensing. 47 (9): 2996-3007.