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Introduction to GlobSnow Snow Extent products with considerations for accuracy assessment

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Abstract

The European Space Agency's Data User Element (DUE) project GlobSnow was established to create a global database of Snow Extent and Snow Water Equivalent. The Snow Extent (SE) product portfolio provided within ESA DUE GlobSnow (2008–2014) is introduced and described, with a special focus on the Daily Fractional Snow Cover (DFSC) of the SE version 2.0 and its successor 2.1 released in 2013–2014. The fractional snow retrieval uses the SCAmod method designed ecpecially to enable accurate snow mapping including forests. The basics of the methodology are presented, as well as the cloud screening method applied in SE production. Considerations for future validations together with discussion on some current issues and potential inaccuracies are presented. One focus of the investigation is on the representativeness of reference FSC generated from Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data, with a particular interest in forested areas. Two methods for reference data generation are investigated. When comparing the GlobSnow Daily Fractional Snow Cover to these reference data, we try to identify how the comparison reflects the possible inaccuracies of the DFSC and to define the conditions where the reference data are not representative. It is obvious that the evaluation result strongly depends on the quality of the reference data, and that the two methods investigated cannot provide representative reference data for dense forests. For fully snow-covered dense conifer forest area in Finland, a Root Mean Squared Error of 20–30% was obtained from comparisons although DFSC indicated full snow cover correctly. These first evaluations would indicate a good performance of GlobSnow SE products in forests; however, this does not necessarily show up in validations due to the non-representativeness of the reference data. It is also concluded that GlobSnow SE products are sensitive to the representativeness of the applied SCAmod parameters and that FSC overestimations may occur in dense forests. GlobSnow SE products are available at www.globsnow.info/se/.

Keywords: Snow extent, Fractional snow cover, ATSR-2, AATSR, forest, Northern Hemisphere, GlobSnow

1. Introduction

Reliable information on seasonal, inter-annual and long-term changes in snow extent and snow mass is important for climate change studies and water management (e.g. Choi et al., 2010; Gong et al., 2007; Kite and Pietroniro, 1996; Schmugge et al., 2002). The two commonest snow variables detected by means of Earth observation are Snow Extent (SE) – featuring binary 'snow/non-snow' information or sub-pixel Fractional Snow Cover, FSC – and Snow Water Equivalent (SWE). Snow extent is typically derived from optical remote sensing data using single or multi-band reflectance data in the visible and near-infrared region, while snow water equivalent can be retrieved with passive microwave techniques.

The European Space Agency's Data User Element (DUE) project GlobSnow was established to create a global database of Snow Extent and Snow Water Equivalent. GlobSnow-1 was launched in 2008 and candidates for the Climate Data Record (CDR) on SE and SWE were introduced in 2011. These prototype versions were further developed in the sequel project GlobSnow-2 (2012–2014). This paper introduces the current GlobSnow SE products (versions 2.0 and 2.1) with a specific focus on daily product featuring fractional snow cover, and describes the methodology for FSC retrieval.

A very commonly used snow database is the suite of NASA MODIS (Moderate-Resolution Imaging Spectroradiometer) snow products (Hall et al., 2002; Riggs et al., 2006), archived and distributed by NSIDC (National Snow and Ice Data Center, US). The MODIS snow products have been extensively validated by the research community (e.g. Ault et al., 2006;Hall and Riggs, 2007; Huang et al., 2011; Rittger et al., 2013; Wang et al., 2008); e.g. Rittger et al. (2013) report a Root Mean Squared Error (RMSE) ~23% (FSC %-units) for Collection 5 MOD10A1 fractional snow. This agrees with the results by Metsämäki et al., (2012) where a comparison between Collection 5 MOD10_L2 fractional snow and *in situ* FSC observations in Finland resulted in an RMSE of 20%. As for all currently available methods, the presence of forest canopy poses a problem for MODIS snow retrievals, since the canopy obscures the sensor's view of the ground. Several methodologies have been developed to better adjust to the presence of forest, but the problem remains unsolved (Hall and Riggs, 2007; Klein et al., 1998; Rittger et al., 2013; Vikhamar and Solberg, 2003, Dietz et al., 2012).

As forests comprise vast portions of seasonally snow-covered regions of the Northern Hemisphere, this is a serious issue.

The GlobSnow SE method development has been particularly focused on fractional snow retrievals in forested areas using ESA ERS-2/ATSR-2 (Along Track Scanning Radiometer) and Envisat/AATSR (Advanced Along Track Scanning Radiometer) data. Based on the evaluation of three different candidate methods, the semi-empirical reflectance model-based method *SCAmod* by Metsämäki et al., (2005) was chosen to be applied to plains while the linear spectral unmixing method *NLR* by the Norwegian Computing Center NR (Solberg and Andersen, 1994; Solberg et al., 2006) was to be applied to mountain areas (the borderline as indicated by a mountain mask). Using two different methods, however, produced inconsistencies at the mountain borderlines (Solberg et al., 2011). Therefore it was decided that only one method would be applied, instead of two. The SCAmod method was found to provide approximately similar accuracy as NLR for mountains and non-forested plains while providing a superior performance for forests, so it was chosen for application to the entire geographical domain of GlobSnow. Indeed, the challenge with GlobSnow has been the expansion of an (originally) regionally applied method to a hemispheric scale.

In the present paper we present first comparisons between GlobSnow daily fractional snow cover products and snow maps generated using high resolution Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data. The aim is not to present an actual validation; instead, we provide considerations for the accuracy of GlobSnow products in different land covers and how this reflects on the comparison results. Particularly, the feasibility of two different methods for generating reference FSC from TM/ETM+ data is evaluated. These evaluations aim at a better understanding of how the validation results depend on the methodology chosen for reference data generation. The findings will support future validation and intercomparison work.

2. GlobSnow SE product overview

The GlobSnow SE product portfolio includes maps of Fractional Snow Cover (FSC, range 0–100% or 0–1) on a 0.01º×0.01º geographical grid and they cover the Northern Hemisphere in latitudes 25ºN–

84ºN and longitudes 168W–192E. 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.

The ATSR-2 is a seven channel instrument providing visible and near-infrared measurements at 1 km spatial resolution. The ATSR-2 was successfully launched on board ESA's ERS-2 spacecraft in 1995 and provided data until 2008. Its successor, the AATSR started operations in March 2002 and provided data until 2012. Swath width for both these sensors is only ~500 km so complete spatial coverage at mid-latitudes cannot be achieved daily. The relevant bands for GlobSnow SE are Band 1 (0.545–0.565 µm) and Band 4 (1.58–1.64 µm) used for FSC retrievals; thermal bands 5, 6 and 7 centered at 3.7 µm, 10.85 µm and 12 µm, respectively, are used for cloud screening. The input ATSR-2/AATSR data used for SE v2.0 production are from the ESA 3rd full reprocessing exercise, which had the new datasets released during late 2013. It was found later that v2.0 SE products whenever based on AATSR suffer from poor geolocation accuracy; after reprocessing, this problem is not present in SE v2.1.

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 Metsämäki et al., (2014).

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).

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 (only far north within a day), the satellite observations applied are those acquired under the highest solar elevation. The FSC is provided only for observations at sun zenith angle < 73º. 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 % ≤ FSC ≤ 10 %
- 10 % < FSC ≤ 50 %
- 50 % < FSC ≤ 90 %
- 90 % < FSC ≤ 100 %

Weekly and monthly products based on D4FSC are also provided, with same specifications as for daily products. The dataset is available at http://www.globsnow.info/se/. Fig. 1 presents an example of daily, weekly and monthly SE products for April 2006.

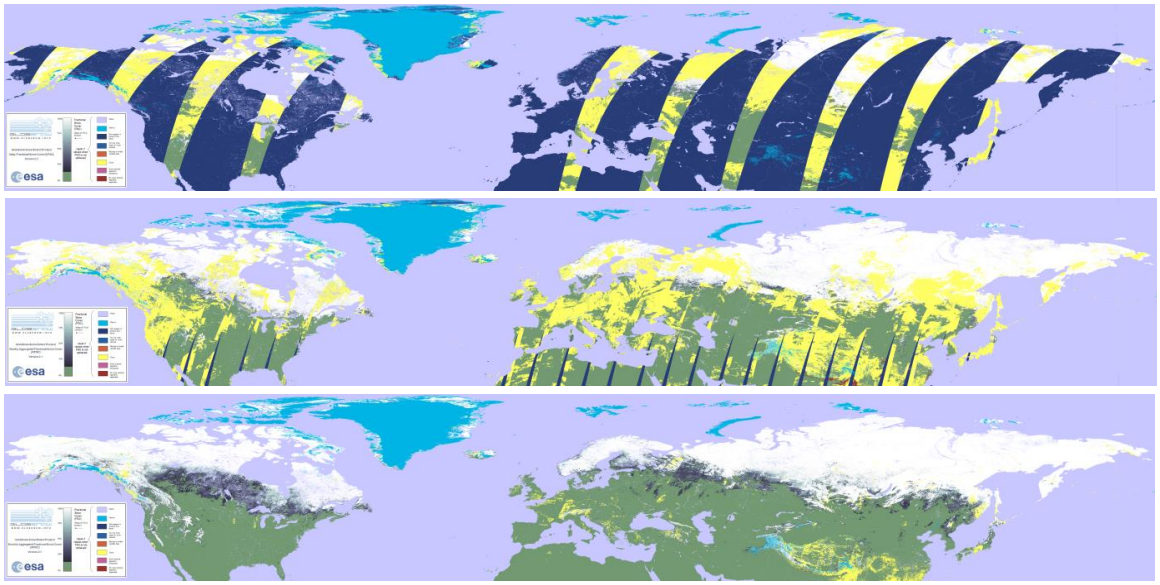


Figure 1. A sample set of GlobSnow v2.1 SE products for April 2006. *Top*: daily product 13 April, *Middle*: weekly product 15 April, *Bottom*: monthly product.

The GlobSnow SE daily product DFSC is characterized by data gaps due to the narrow swath width of the ATSR-2 and AATSR sensors. This, together with the 3 days revisit time, implies that 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). This has implications for the feasibility of the products, for instance in climate change studies. However, these issues are not covered by the present paper as the focus is on the daily product.

3. Description of the FSC retrieval method

3.1 SCAmod and additional rules

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 reflectance observations under conditions that highlight the presence of forest canopy – namely in the presence of full snow cover on the ground. Given the transmissivity can be determined with an appropriate accuracy, SCAmod enables the consideration of the masking effect of forest canopy in fractional snow cover estimation (Metsämäki et al., 2005, 2012). SCAmod was first developed for fractional snow mapping in Finland representing a variety of boreal landscapes including dense evergreen coniferous forests. At the early stage of the GlobSnow-1 project, SCAmod was found to also be feasible for hemispheric FSC retrievals, provided the transmissivity can be determined on a hemispheric scale.

SCAmod expresses the observed reflectance as follows:

$$\rho_{\lambda,obs}(FSC) = (1-t_\lambda^2) * \rho_{\lambda,forest} \quad + \quad t_\lambda^2 * \left[FSC * \rho_{\lambda,snow} + (1-FSC) * \rho_{\lambda,ground} \right] , \qquad (1)$$

where $\rho_{\lambda,snow}$, $\rho_{\lambda,ground}$ and $\rho_{\lambda,forest}$ are generally applicable pre-determined reflectances of (wet) snow, snow-free ground and forest canopy at wavelength λ, respectively. $\rho_{\lambda,obs}$ stands for the observed reflectance from the calculation unit area. t_λ^2 stands for the apparent two-way transmissivity of the unit area.

FSC (range 0–1 here) is solved from (1) as follows:

$$FSC = \frac{\frac{1}{t_\lambda^2} * \rho_{\lambda,obs} + (1 - \frac{1}{t_\lambda^2}) * \rho_{\lambda,forest} - \rho_{\lambda,ground}}{\rho_{\lambda,snow} - \rho_{\lambda,ground}}. \quad (2)$$

In GlobSnow, SCAmod employs top-of-atmosphere reflectance acquisitions of ATSR-2/AATSR Band 1 (545–565nm) as $\rho_{\lambda,obs}$. The feasible values for the three reflectance constituents are based on MODIS band 4 (550nm) reflectance observations and field spectroscopy, see section 3.2. Transmissivity is derived from (1) 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.

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, due to a prevailing snow reflectance higher than that applied in the model. This is the case for dry snow introducing higher reflectance than that of melting (wet) snow, for example. 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.

An additional test for identification of snow-free conditions is applied to avoid false snow detection if the observed reflectance from snow-free terrain is higher than assumed by the model. The Normalized Difference Snow Index (NDSI, Riggs et al., 1994) is used to identify confident snow-free cases. Since the NDSI decreases with the decreasing snow fraction (Hall et al., 1995) it is possible to determine a threshold to identify a snow-free situation. The value 0.4 (or 0.1 for forested areas) as

proposed by Klein et al., (1998) however, is not feasible for SCAmod purposes, as the intention is to also identify small snow fractions accurately without thresholding that is too conservative. A threshold of -0.02 is used in GlobSnow:

IF NDSI < -0.02 THEN FSC = 0. (3)

This threshold was empirically derived from NDSI observations from Terra/MODIS imagery over Finland, using weather station data and information on general climatology to verify snow-free conditions soon after snow disappearance. Using a slightly negative value is also supported by findings by e.g. Xin et al., (2012) and Niemi et al., (2012), reporting negative values for dense forest areas particularly with non-nadir view angles. A very low NDSI – although above zero – is also accepted by the MOD10_L2 fractional snow algorithm (Salomonson and Appel, 2006) for very low snow fractions.

Temperature screening is applied to avoid false snow identifications caused by highly reflective non-snow targets like certain non-identified cloud types or warm bright mineral surfaces. A pixel is designated 'snow-free' if its temperature > threshold. Temperature screening is applied e.g. in the provision of MODIS Collection 5 snow products where a temperature threshold of 283 K is used (Hall et al., 2002; Riggs et al., 2006). Although the temperature screening was later found to cause low snow fractions to 'disappear', particularly in rocky mountain areas where snow-free patches may raise the surface temperature above the threshold (Riggs and Hall, 2012), the screening is used in GlobSnow v2.0 and v2.1 SE production. However, to reduce false snow omissions, the threshold was set higher than 283 K; it is based on a single band (band 7, centered at 12μm) approximation of the surface brightness temperature:

IF temperature > 288 K THEN FSC=0. (4)

3.2 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.

Here we present the principles for determination of these; a more detailed description is given in Metsämäki et al., (2014). 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 the ones provided by MODIS, so this is considered a reasonable approach.

3.2.1 Snow and forest canopy reflectance

The generally applicable value for snow reflectance $\rho_{\lambda,snow}$ in eq. (1) is empirically derived from i) MODIS band 4 reflectance observations from snow-covered non-forested areas (Metsämäki et al., 2012) and ii) at-ground spectral measurements conducted in Finland (Salminen et al., 2009; Niemi et al., 2012). For the latter, conversion from at-ground reflectance to top-of-atmosphere reflectance was conducted using the Simplified Method for Atmospheric Correction (SMAC) (Rahman and Dedieu (1994); Berthelot, 2003) with the standard atmosphere adjusted to Finnish springtime conditions.

It is recognized that using only one value for snow reflectance does not correspond to the large variation in snow reflectance caused by varying grain size, impurities and thickness (e.g. Dozier et al., 2009; Nolin and Dozier, 2000; Painter and Dozier, 2004; Warren; 1982). In the provision of GlobSnow SE, these variances are propagated in the uncertainty of FSC, while the applied constant value ($\rho_{\lambda,\mathrm{snow}}$=0.65) is considered a reasonable approximation for the average case.

Forest canopy reflectance $\rho_{\lambda,forest}$ in eq. (1) refers to totally opaque forest canopy. Since such canopies are not easy to identify, we have to rely on observations from canopies we assume are close to opaque. The applied value was mainly derived from MODIS reflectance observations from carefully selected very dense boreal forests over Finland and Russia (Metsämäki et al., 2012), but also from reflectance measurement of thick layers of Scots pine branches at laboratory condition (Niemi et al., 2012). A value of 0.08 for $\rho_{\lambda,forest}$ is considered reasonable for FSC estimation.

3.2.2 Snow-free ground reflectance

The earlier GlobSnow v1.2 SE implementation of SCAmod uses a fixed value $\rho_{\lambda,ground}$ =10% (0.10) for the visible wavelengths around 555 nm. This value was derived by sampling MODIS top-of-atmosphere reflectances over representative areas as well as from at-ground reflectance measurements with portable spectrometer (Metsämäki et al., 2012; Salminen et al., 2009). In practice, the spatial and temporal variability of $\rho_{\lambda,ground}$ causes an error contribution to FSC estimation. In v2.0 and v2.1 SE production this variability is considered by determination of spatially varying post-winter snow-free ground reflectance map to be applied by SCAmod as auxiliary data. For seasonally snow-covered areas in the Northern Hemisphere, the snow-free ground reflectance statistics were determined using reflectance observations and land cover information (ESA GlobCover, Bicheron et al., 2008) for training areas in Europe and in North America. The observations representing post-melt (assumed mostly wet) snow-free ground were extracted from the MODIS reflectance time-series using methodology by Salminen et al., (2013). The extracted pixel-wise values were then related to the GlobCover data to generate class-stratified snow-free ground reflectance statistics. The swath level MOD02HKM data were calibrated to top-of-atmosphere reflectances and processed into a 0.005º geographical grid.

For the majority of the classes, snow-free ground reflectance statistics were derived from the European training area, while for 4 classes, separate analyses were made for North America and Europe. For regions with ephemeral snow, the snow-free ground reflectance statistics were determined by analysing selected MOD09 products for Africa and Asia. MODTRAN atmospheric code (Anderson et al., 1995; Berk et al., 1989) simulations were applied for conversion to top-of-atmosphere reflectances. For the classes that remained not analyzed (e.g. forests)**,** a snow-free ground reflectance of 10% was assigned, based on earlier implementations of SCAmod (Metsämäki et al., 2012). The statistics gained, combined with the GlobCover data, were employed to generate the spatially varying snow-free ground reflectance map, presented in Fig. 2.

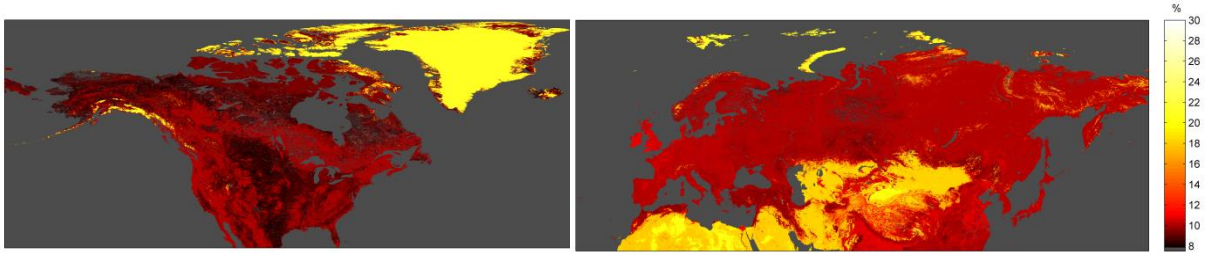


Figure 2. Snow-free ground reflectance maps applied in the GlobSnow v2.0 and v2.1 SE production: North America (*Left*) and Eurasia (*Right*).

3.2.3 Apparent forest transmissivity

The transmissivity for a target area can be established using reflectance data acquired under full snow cover conditions (Metsämäki et al., 2005). At a hemispheric scale, this approach would be very laborious to accomplish; therefore, a new method for generating the transmissivity map using global land cover data too was developed for GlobSnow (Metsämäki et al., 2012). 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 the present GlobCover classes; 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 through 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 transmissivity map was applied in the provision of GlobSnow v1.2 SE products. Although the general performance of this approach was considered good, some underestimations were identified for very dense forests (Solberg et al., 2011). Comparisons between the original MODIS-derived transmissivities and the GlobCover-based transmissivities revealed that the method could not fully capture the densest forests but these were typically assigned with transmissivity that was too high. Further analysis indicated that most problems occurred with four particular boreal forest classes, each class representing dense and moderate canopies. This was seen in the class-stratified tranmissivity statistics as high standard deviation. As a result, the average transmissivity gained did not properly represent either of the forest types. Hence it was concluded that the GlobCover-based approach would benefit from external data accounting for the forest density. For this purpose, visible white-sky albedo as provided by ESA GlobAlbedo (Müller et al., 2012) was

selected. Although there is an increase in albedo over snow-covered boreal forests (snow on or beneath the canopy), these albedos are clearly lower than those from non-forested areas (Barlage et al., 2005; Moody et al., 2007). The analysis between the albedo from selected wintertime 8-day composites – with snow cover on terrain prevailing – 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. It should be noted that this technique is valid only in the presence of full snow cover, corresponding to transmissivity calculations as presented in Metsämäki et al., (2005, 2012). Therefore, GlobSnow SWE products (Takala et al., 2011) were used to identify the snow-covered areas before launching the correction procedure. The two-way transmissivity map for the Northern Hemisphere is presented in Fig. 3.

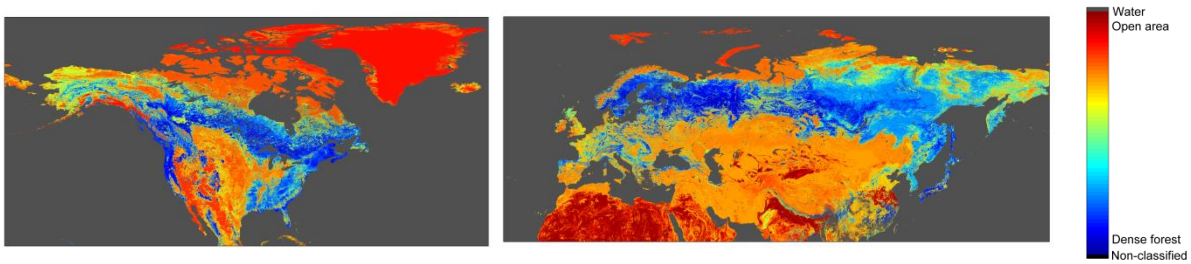


Figure 3. Map of the apparent two-way forest transmissivity map (t^2) for North America (*Left*) and for Eurasia (*Right*).

3.3 Determination of the FSC uncertainty

The estimated uncertainty for FSC is provided as a separate layer in SE products. This statistical error accounts for the uncertainty due to the variations in the SCAmod parameters. At the moment, the uncertainty layer does not include systematic error contribution as this would require extensive *in situ* validation work which has not yet been compiled. Hence, the SE uncertainty corresponds to an unbiased standard error of an FSC estimate in %-units (Metsämäki et al., 2014). It is determined by applying an error propagation analysis to the inverted SCAmod reflectance model (Metsämäki et al., 2005; Salminen et al., 2013). The applied error propagation analysis considers the variability of the different factors affecting the satellite-observations in various measurement conditions, these

variations being determined during or straight after the snow season. This implies that the uncertainty does not particularly include intra-annual variations – however it does depend on the level of FSC.

The relevant error contributors in FSC retrieval with SCAmod are the variabilities in snow reflectance, forest transmissivity, forest canopy reflectance and snow-free ground reflectance. For the transmissivity, these variations are derived from the MODIS top-of-atmosphere reflectances (view zenith angles 0–50º in forward scatter and backscatter directions, sun zenith angles 61–75º) employed in the transmissivity generation for the training area in Europe (Metsämäki et al., 2012). For snow, the standard deviation is derived from at-ground spectral measurements mainly made in Sodankylä, Finland. These measurements were conducted for different grain sizes and depths of the snowpack (Niemi et al., 2012; Salminen et al., 2009). Standard deviations for snow-free ground reflectances are derived from MODIS acquisitions as described in Salminen et al., (2013); the view zenith angles and sun zenith angles ranging as for the transmissivity, depending on the GlobCover class. The uncertainty for monthly product MFSC is calculated as an average of uncertainties of the daily products within the corresponding period; an example for April 2006 is presented in Fig. 4.

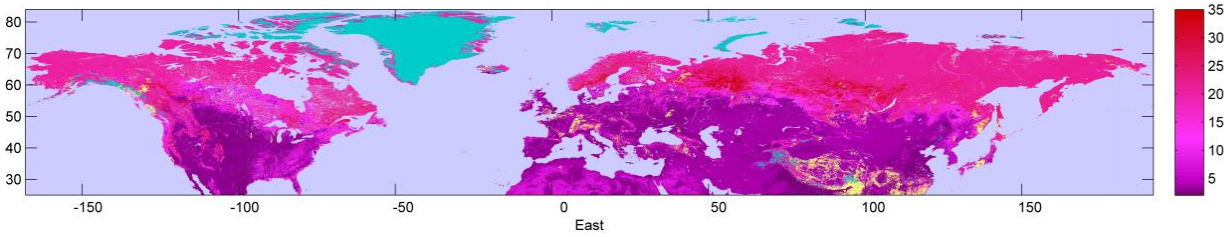


Figure 4. Uncertainty layer for v2.1 SE Monthly product, April 2006. Statistical error (non-biased standard error) for each FSC estimate is provided in FSC %-units. A yellow color indicates cloudy areas, cyan indicates non-classified areas of permanent snow and ice (see class 'Glacier' in Fig. 1), according to the GlobCover data.

4. Cloud screening

Several cloud detection methods for optical remote sensing data with particular considerations for snow/cloud discrimination have been developed (e.g. Ackerman et al., 1998; Allen, 1990; Khlopenkov et al., 2007; Knudby et al., 2011; Saunders and Kriebel, 1988). The problem, however,

has not been completely solved. The cloud/snow confusion causing false cloud commissions at the edges of snow cover in particular may be a problem (Hall and Riggs, 2007; Solberg et al., 2011; Tekeli et al., 2005). Since the AATSR operational cloud mask is reported to have difficulties over snow-covered terrain (e.g. Plummer et al., 2008), a new cloud screening method was established for the generation of the GlobSnow SE v1.2 data record (Metsämäki et al., 2011). A simple and computationally low-cost binary (cloud/clear) classifier method was based on ATSR-2/AATSR data without any external data source was named SCDA (Simple Cloud Detection Algorithm). Based on the evaluations for the GlobSnow SE v1.2 dataset, it was later concluded that improvements for cloud screening were still necessary. Therefore, a new cloud screening method called SCDA2.0, was developed and implemented for the SE v2.0 processing chain. SCDA2.0 was designed to be used for optical and infrared data from sensors such as Terra/MODIS, ERS-2/ATSR-2, ENVISAT/AATSR, NPP Suomi/VIIRS and the future Sentinel-3 SLSTR. The method uses wavelength bands 550 nm, 1.6 µm, 3.7 µm, 11 µm and 12 µm, common for these sensors. Fig. 5 presents the cloud screening scheme, with these bands referred to as R550, R1.6, BT3.7, BT11 and BT12, correspondingly.

The methodology is based on the several empirically determined decision rules, determined from selected training areas representing (by visual judgement) clouds, snow-covered terrain, partially snow-covered terrain and snow-free terrain. NPP Suomi/VIIRS and Terra/MODIS aqcuisitions from several dates and from different regions over Northern Hemisphere provided the training data. The decision rules were determined with a heuristic approach by investigating the distributions of features – reflectances, brightness temperatures and their-related ratios – in different projections. Fig. 5 presents the cloud screening scheme. It should be noted that the success of cloud screening is based on visual evaluation of several (other than training data) MODIS, VIIRS and AATSR acquisitions, i.e. no *in situ* cloud observations were used for the assessments. Instead, a comparison against the cloud mask provided with the MOD10_L2 fractional snow product was made for several MODIS swaths, particularly for acquisitions made during snow melt period.

The development work for SCDA2.0 was intended particularly for identification of clouds throughout potential snow seasons for such regions where snow events are typical. Identification of clouds over regions without even ephemeral snow is therefore not given any left specific attention,

which means that thin semi-transparent clouds over areas confidently assumed to be snow-free may not be classified as cloud. This kind of 'liberal' mask would retain more area for snow/non-snow mapping purposes. As a drawback, some non-detected clouds still may confuse the snow mapping method, leading to false snow commissions during summer months. In most cases however, non-detected clouds in summertime images are assigned 'snow-free' by the FSC retrieval method.

Finally, the original cloud mask is enhanced by expanding by a width of 1–3 pixels. This would diminish the presence of partly cloud-contaminated pixels at the cloud edges and also removes part of the shadows cast by clouds. In practice, expansion is carried out by convolving the cloud mask with a 7×5 sliding window which is asymmetrically weighted to expand more to the north-west (shadow casting) side of the clouds.

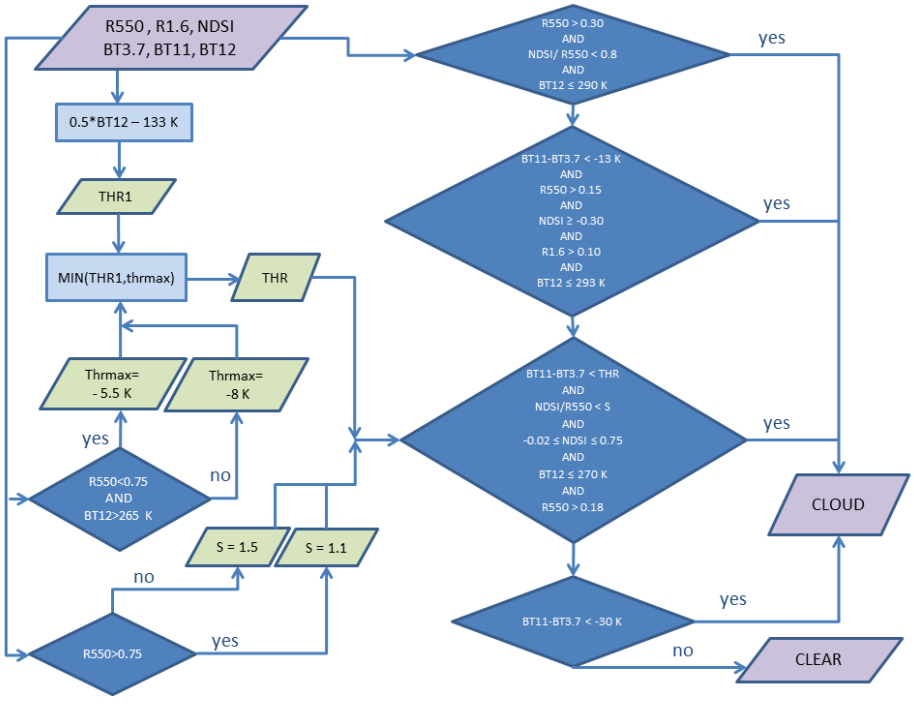


Figure 5. SCDA2.0 cloud scheme used in GlobSnow v2.0 and v2.1 SE production.

5. Considerations for accuracy assessment

5.1 Uncertainty originating from the FSC retrieval method

The SCAmod reflectance model, when applying several pre-fixed parameters either as spatially varying or static values, is sensitive to the representativeness of these parameters. For instance, only

one generally applicable value for snow reflectance is currently used. Considering snow reflectance varies highly with snow properties e.g. grain size, black carbon (BC) concentration and depth of the snowpack as well as with viewing/illumination conditions, this simplification has implications for the accuracy of FSC retrievals. For instance, the decrease in snow visible albedo (or reflectance) can be close to 40% at very high black carbon concentrations or with a very thin snowpack (Warren, 2013). Ignoring this strong decrease, SCAmod would produce an almost 50% (relative) FSC underestimation compared with what would be gained by applying the decreased 'true' value. Similarly, the non-representativeness of snow-free ground reflectance or forest canopy reflectance increases the inaccuracy of FSC retrievals. As described in Section 3.2.2, the snow-free ground reflectance map is based on observations at the time of snow melt-off and therefore does not reflect the seasonal changes in the snow-free ground reflectance. In addition to this, some of the classes were directly assigned a value of 10%. This has potential implications for the accuracy of FSC retrievals. If the true level of local snow free ground reflectance differs from the applied static value, a systematic error (bias) is introduced in FSC retrievals, see Salminen et al., (2013), their Eq. 4 (note that there is a printing error; subtraction of FSC is missing at the end of Eq. 4). The impact of non-representative snow-free ground refelctance is demonstrated in Section 5.3 – case study #3.

There are potential inaccuracies originating from the idea of SCAmod's forest compensation. In hemispheric-scale comparisons against MODIS Collection 5 MOD10_L2 fractional snow products, the GlobSnow project team has found that GlobSnow SE products provide higher FSC for boreal forests than MODIS does. During high snow season this is probably in favor of GlobSnow SE as MODIS seems to underestimate FSC in boreal forests (Metsämäki et al., 2012) while SCAmod shows less underestimation. Yet SCAmod may lead to overestimation of FSC in very dense forests with low transmissivity. This is because at low transmissivity, forest is a relatively dark target with or without under-canopy snow, and the reflectance model allows very limited dynamics for the observed reflectance $\rho_{\lambda,obs}$ (see Eq. 1) in the FSC range of 0–100%. Accordingly, $\rho_{\lambda,obs}$ (FSC=0%) is only a few steps from $\rho_{\lambda,obs}$ (FSC=100%), both being low values. As a consequence, a small increase in

reflectance (e.g. by atmospheric aerosols) shows up as a strongly increased FSC estimate. These effects will be evaluated in further hemispheric scale validations and cannot be covered in this paper.

FSC retrievals are also sensitive to the representativeness of the local transmissivity. The possible non-representativeness mainly originates from the technique used in the generation of NH transmissivity (see Section 3.2.3): for a certain class, a high standard deviation of the MODIS-derived transmissivities implies that the mean of this distribution is a poor estimate for a class-stratified value. This issue is discussed and demonstrated in Metsämäki et al., (2012), where the impact of using GlobCover-based transmissivity instead of MODIS-derived transmissivity is demonstrated for selected regions in western Eurasia. For these regions however, only a minor decrease in RMSE was found, when FSC retrievals were compared with TM/ETM+ reference FSC.

One source of inaccuracy is the misclassification/outdated information in GlobCover, as the transmissivity map and snow-free ground reflectance map are generated using GlobCover to obtain the NH coverage. For instance, a prominent error occurs if GlobCover indicates dense forest for a pixel that is actually forest-free (e.g. after clearcutting which does not show up in GlobCover). In such case, FSC is highly overestimated throughout the season.

It should also 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 also emphasized by the applied limitation for the sun zenith angle (max. 73º 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 however not crucial for snow mapping during the melting period in boreal forest and tundra zones and of course has no impact on mid-latitude snow retrieval.

5.2 Generation of reference FSC from Landsat TM/ETM+ imagery

Hemispheric-scale snow maps can be evaluated by comparing them to snow information derived from high-resolution imagery, with the assumption that these provide an appropriate approximation of the 'truth'. This is in practice the only option as there are only very limited *in situ* data particularly on fractional snow cover are available. It is obvious that the evaluation result strongly depends on the

quality of the reference data. When comparing the GlobSnow DFSC to these reference data, we try to i) identify how the comparison reflects the possible inaccuracies of the DFSC and ii) define the conditions where the reference data are not representative.

Due to the good availability of Landsat TM/ETM+ data, these have been commonly used for evaluations of coarser resolution snow products (e.g. Metsämäki et al., 2012; Painter et al., 2009; Rittger et al., 2013; Vikhamar and Solberg, 2003). Two methods for reference FSC determination from TM/ETM+ data are investigated here: i) the fractional snow method by Salomonson and Appel, (2006) and ii) the binary snow retrieval method by Klein et al., (1998). These methods provide snow information for high-resolution pixels, and the information can be aggregated into coarse resolution grid to 'simulate' the FSC estimates under evaluation. In addition to this, a reasonable candidate for reference FSC generation would be spectral unmixing providing high accuracy data (e.g. Painter et al. 2009; Rittger et al. 2013), but due to its more complex implementation spectral unmixing was excluded in this study.

The fractional snow retrieval method by Salomonson and Appel (2006), referred to as the *Salomonson and Appel method* hereafter, is based on a statistical linear regression between FSC and the NDSI (FSC = -0.01+1.45×NDSI); determination of globally applicable regression coefficients for computing FSC from the NDSI was carried out using several Landsat TM scenes in different locations in the Northern Hemisphere. This is the baseline method in the MODIS MOD10A1 and MOD10_L2 fractional products (Hall et al., 2002; Riggs et al., 2006). From MODIS, this methodology is reported to provide FSC with a mean absolute error of < 10% (Salomonson and Appel, 2004). While using this technique for TM/ETM+ data, we assume that the same accuracy can also be reached with higher resolution data. Although the NDSI regression technique has a weaker performance for dense forest areas than for open or sparsely forested regions because a lower NDSI is observed from forests (Salomonson and Appel, 2004; Metsämäki et al., 2012; Niemi et al., 2012) it was decided here to use this approach uniformly for all TM/ETM+ scenes. However, the presence of forest must be taken into consideration when interpreting the results.

The binary snow mapping method by Klein et al., (1998) – referred to as the *Klein method* hereafter – is based on NDSI-thresholding, with additional rules utilizing the NDVI (Normalized

Difference Vegetation Index) as well as some reflectance thresholds. This method classifies a pixel as 'snow' if its snow fraction is > ~50%, the threshold depending on the land cover. After binary mapping in TM/ETM+ nominal resolution, the coarser resolution FSC can be retrieved by averaging the binary data. Although this technique may result in biased FSC, providing underestimations at low snow fractions and overestimations at high snow fractions (Rittger et al., 2013), these data serve as complementary information for our efforts to assess the feasibility of TM/ETM+ data for SE product evaluation. It has also been found to identify snow in forests better than the Salomonson and Appel method (Salomonson and Appel, 2004; Rittger et al., 2013).

Overall, the TM/ETM+ processing includes calculation of top-of-atmosphere reflectances for visible and near-infrared band 2 (0.52–0.60 µm), band 3 (0.63–0.69 µm), band 4 (0.76–0.90 µm) and band 5 (1.55–1.75 µm) to provide the NDSI and NDVI, as well as brightness temperature for band 6 (10.40–12.50 µm). Band 6 is applied to identify warm surfaces so that whenever the temperature exceeds 288 K, the pixel is assigned as 'snow-free' (this is an addition to the Salomonson and Appel method and to the Klein method). Topographic correction is applied to the scenes with varying elevations using the Ekstrand method (Ekstrand, 1996). The data is reprojected and resampled to a 0.00025º grid in the WGS-84 system. Then the Salomonson and Appel method or Klein method is applied. These high resolution data are then aggregated to 0.01º pixel size to match the pixel size of the GlobSnow SE product. In this paper, the resulting FSC maps are hereafter referred to as *FSCklein* and *FSCsalapp*. Manually masked clouds and water pixels (according to the GlobCover classification) were excluded in the analysis.

5.3 Evaluations of GlobSnow DFSC in case of different land covers

Five Landsat TM/ETM+ scenes were processed for comparison to the GlobSnow DFSC. These scenes were selected to represent different land covers, aiming for preliminary assessment of the product performance in general. In these assessments, the feasibility of the two methods described above for reference data generation is addressed. For two of the scenes, also comparison to the MODIS Collection 5 MOD10_L2 fractional snow product is presented.

The differences between estimated and independent reference FSC (N cases) are analyzed using root-mean-squared-error (RMSE) and Bias as validation metrics:

$$RMSE = \sqrt{\frac{1}{N}\sum (FSC_{estimated} - FSC_{reference})^2} \quad (5)$$

$$Bias = \frac{1}{N}\sum (FSC_{estimated} - FSC_{reference}) \quad (6)$$

where $FSC_{estimated}$ and $FSC_{reference}$ refer to estimated and reference FSC at 0.01^o pixel size.

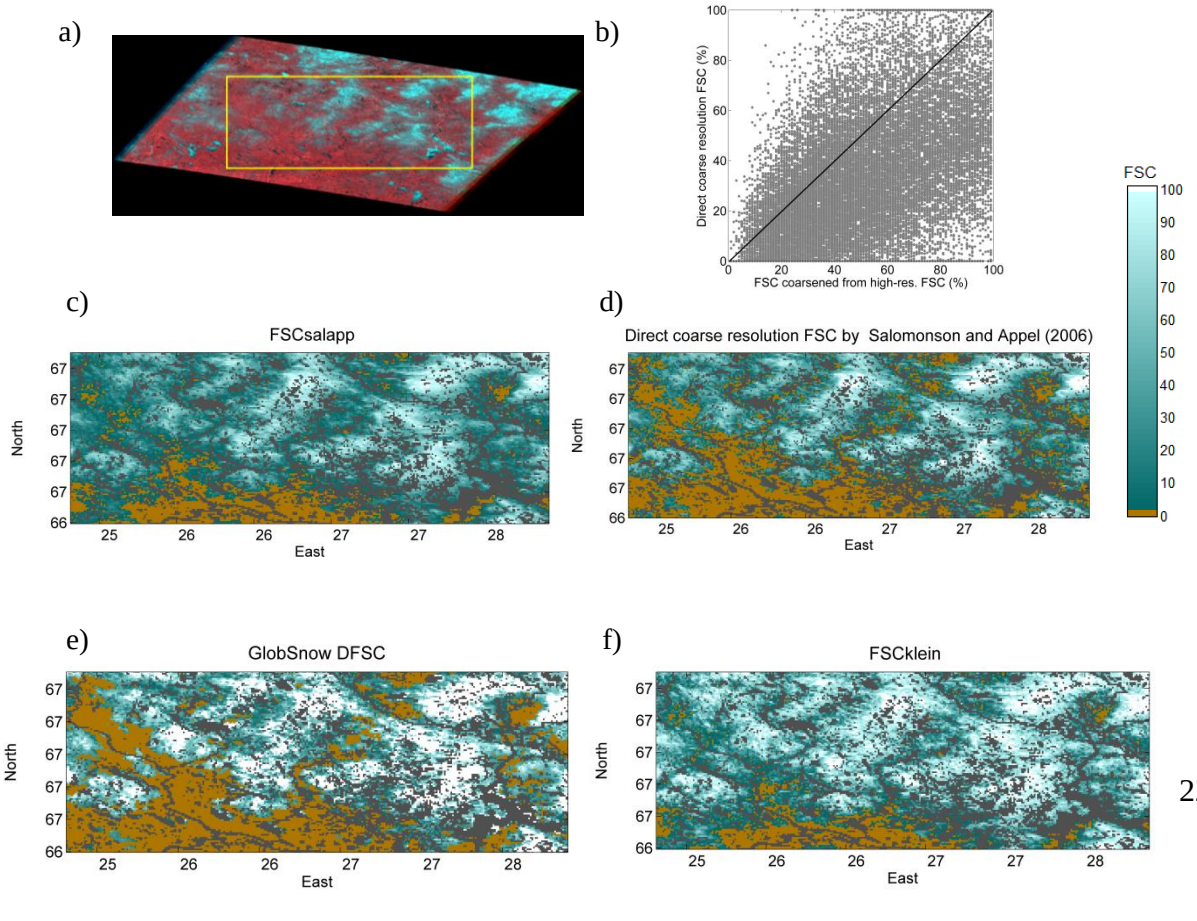
When using these metrics, it should be noted that the idea of using aggregated high-resolution snow data (either binary or fractional) to 'simulate' coarse resolution FSC includes a certain limitation. Namely, with high-resolution data it is possible to identify snow in just one pixel which then shows up in the aggregated FSC, but which is too little to create enough of a 'snow' signal derived from the coarse resolution pixel directly. This means that particularly at low snow fractions but also at higher snow fractions, FSC aggregated from high-resolution FSC is persistently higher than direct coarse resolution FSC (here we assume that the signal from coarse resolution pixel is a linear combination of those from the high-resolution pixels; this approximation should be appropriate in this context). This is a typical way of using high resolution data for validations; however the issue of different scales in FSC retrievals is present regardless of the retrieval method applied.

Case study #1: forested region

The reference FSC generation using different methods is demonstrated for TM scene LT51910132006125KIS00 over Northern Finland, May05 2006, see Fig. 6a (yellow rectangle indicates the area extracted for visualization of the FSC-maps in more detail in Figs. 6c-g). ~80% of the scene area is covered by conifer forests. The 13 weather stations distributed throughout the scene area report snow fractions 0–50% (according to the e-code describing the snow coverage in the range of vision of a human observer); stations are located in open areas so higher snow fractions can be assumed for forests where snow usually stays longer (e.g. Metsämäki et al., 2012). This is highlighted by the fact that a snow depth of 0 cm (punctual measurement) is reported at the majority of the stations, even though at the same time the e-code indicates snow. FSCsalapp (Fig. 6c) shows

fractional snow over most of the area, the average scene FSC is 31%. Salomonson and Appel method applied directly to data coarsened to 0.01º pixel size produces less snow as expected (Fig. 6d); the average scene FSC is 27%. Both of these for the entire scene are presented in Fig. 6b. From this simple analysis we can deduce that the differences obtained in the FSC can in principle originate from different scales, not necessarily from the FSC retrieval method itself. This should be considered when interpreting the validation results in general.

The average scene FSC by FSCklein (Fig. 6f) is 48%. The GlobSnow SE (Fig. 6e) shows relatively good correspondence with both TM-based maps but loses some of the low snow fractions, the average scene FSC is 39%. The fact that the GlobSnow DFSC lies between FSCsalapp and FSCklein is expected, as the former tends to underestimate in forests whereas the latter tends to overestimate. For comparison, the MOD10_L2 fractional snow product is also presented in Fig. 6g. It does not agree with Fig. 6d although both maps are based on the same method (the MOD10_L2 produced from the Terra/MODIS acquisition on the very same day) but shows much less snow, most likely due the thermal screen applied after actual FSC retrieval (Riggs et al., 2006). The average scene FSC from the MOD10_L2 is only 10%. Here the MOD10_L2 also shows the typical false cloud commissions at the edge of snow-covered areas (yellow color in Fig. 6g), this problem is alleviated in the GlobSnow DFSC as the SCDA2.0 cloud mask is more liberal.



g)

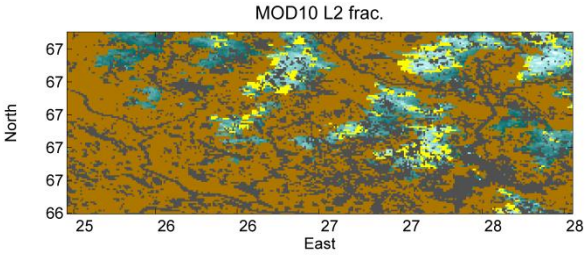


Figure 6. FSC at 0.01º pixel size, for Landsat TM scene area LT51910132006125KIS00, Northern Finland, on May 05, 2005. a) The entire scene as RGB composite of TM-bands 5, 3 and 2, b) FSC's based on applying the Salomonson and Appel method to TM data, either through aggregation of high-resolution pixels (FSCsalapp) or directly to coarsened pixels, c)–d) the corresponding FSC maps, e) the GlobSnow DFSC, f) FSCklein, g) MOD10_L2 fractional product, the yellow color indicates clouds.

Case study #2: non-forested region

In the following case study, the GlobSnow DFSC is compared to fractional snow cover maps from Landsat-5 TM scenes LE71540301999319SGS00 (Kazakhstan, Central Asia, November 15, 1999) and LT50400151999152PAC00 (Nunavut Canada, June 01, 1999), see Fig. 7. Both scenes are characterized by fractional snow cover over terrain that was practically non-forested.

For the Kazakhstan scene (Fig. 7, top pane) comparison of the GlobSnow DFSC and FSCklein would first indicate that the GlobSnow DFSC overestimates the low fractions and underestimates the high snow fractions. However, since FSCklein is typically biased (see above) this would likely be an erroneous interpretation. Indeed, comparison with FSCsalapp shows a better correspondence with an RMSE of 11% and correlation coefficient of 0.94, compared to that of FSCklein (RMSE 15%, correlation coefficient 0.89). It is also likely that the snow-free ground reflectance employed by SCAmod is relatively representative for the Kazakhstan scene, as at low snow fractions no noticeable bias is found. However, the GlobSnow DFSC shows a slightly lower FSC than FSCsalapp, which agrees with the above discussed issue of using different scales in FSC retrieval, see Fig. 6b.

For the Nunavut scene (Fig. 7, bottom pane), the comparison between the GlobSnow DFSC and TM-based FSC's shows good agreement, resulting in an RSME of 13% for FSCklein and FSCsalapp.

The correlation coefficients for FSCklein and FSCsalapp are 0.93 and 0.94, respectively. It is likely that the snow-free ground reflectance applied is not as representative as for the Kazakhstan scene, as low snow fractions are overestimated. Overestimation occurs if the snow-free ground reflectance applied is lower than truly present in the target area. This issue is discussed later in case study #3.

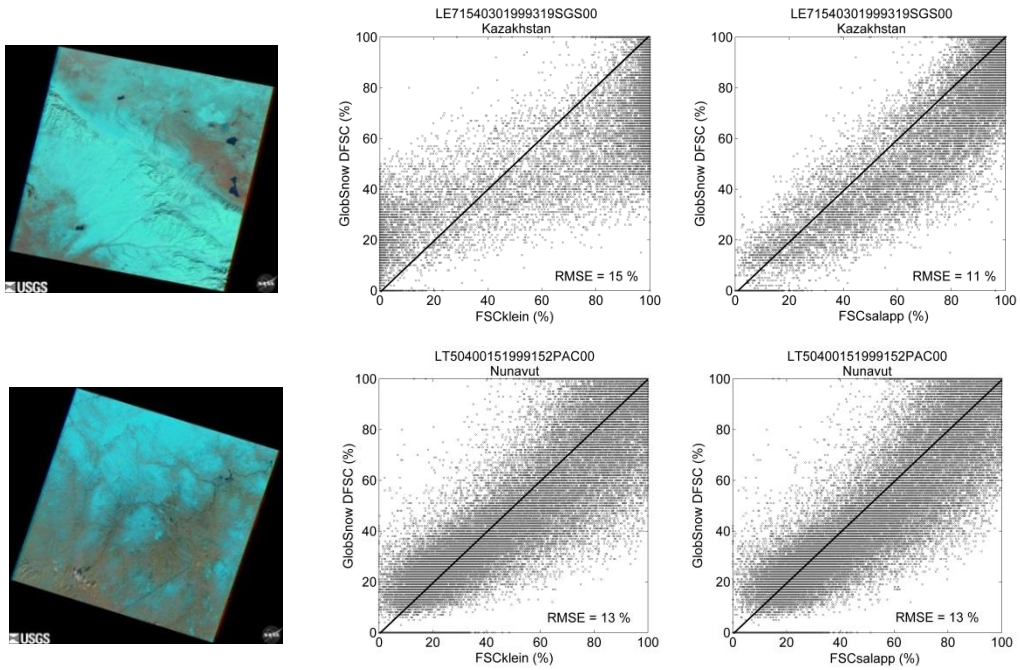


Figure 7. Comparison between the GlobSnow DFSC and two methods for FSC retrieval from TM/ETM+ data over Kazakhstan (top pane) and Nunavut, Canada (bottom pane). *Left*: Browse image, *Middle*: FSCklein, *Right:* FSCsalapp.

Case study #3: non-forested region with considerations for snow-free ground reflectance

In the following case study, the effect of the non-representative value of snow-free ground reflectance on the FSC estimation is demonstrated for TM scene LT5037342006358PAC01 over Utah, on December 24, 2006, see Fig. 8e . The early evaluation of the GlobSnow v2.0 and v2.1 DFSC products indicates that a systematic error (overestimation) is evident for areas of class 130 ('closed to open shrubland' according to GlobCover data) in Western US, where this prevalent class represents sparsely vegetated and semiarid areas in intermontane plateaus. The value of 10% was assigned to this class in the snow-free ground reflectance map. Analysis of local reflectances in the TM scene indicates that the south-eastern part of the scene is characterized by a reflectance level significantly

higher than 10% in snow-free conditions. This would lead to FSC overestimation when applying SCAmod. The DFSC, FSCklein and FSCsalapp are presented in Fig. 8; for comparison, fractional snow provided by the MOD10_L2 for the same day is also presented. Generally, all products show the same spatial distribution for snow. Indeed, the probable overestimation is present in the DFSC as high snow fractions are pronounced, while MOD10_L2 seems to provide a lower FSC than the other three products.

Incidentally, Fig. 8 shows the better performance of the SCDA2.0 cloud screening method for this particular scene. The typical problem of false cloud commissions at the edge of snow-covered terrain (see Section 4) is visible in the MOD10_L2 product, as shown by extensive areas of yellow color. The corresponding cloud mask by SCDA2.0 is clearly lesser in the area, shown in yellow color in the GlobSnow DFSC product and also in TM-based FSC maps.

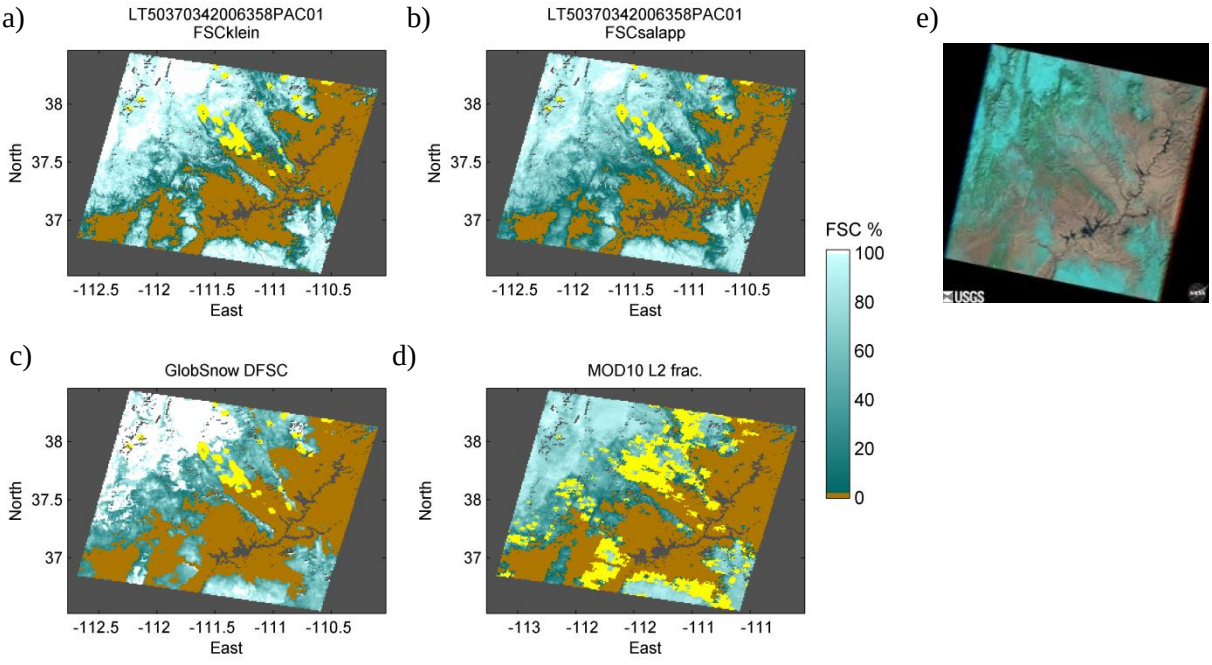


Figure 8. Fractional snow cover maps as provided by a) FSCklein, b) FSCsalapp, c) the GlobSnow DFSC, d) MOD10_L2, for TM scene LT5037342006358PAC01 over Utah, US, on December 24, 2006 (e). The yellow color corresponds to clouds.

The differences between the four products stand out in pixel by pixel comparisons in Fig. 9. Again, FSCklein results in a higher RMSE (20%) than FSCsalapp (16%) when compared with the DFSC.

The very likely overestimation particularly at low snow fractions in the DFSC (see above) is also pronounced in Fig. 9a and 9b as the DFSC practically loses all snow fractions between 0–15%. Comparison between the DFSC and MOD10_L2 (Fig. 9c) indicates relatively good correspondance with an RMSE of 18% and correlation coefficient of 0.92, except again for low snow fractions. Finally, the RMSE for MOD10_L2 when compared with FSCsalapp is 15% (Fig. 9d), again demonstrating the scale problem discussed in 5.2, but having a high correlation of 0.96 which is expected as both are based on the same method.

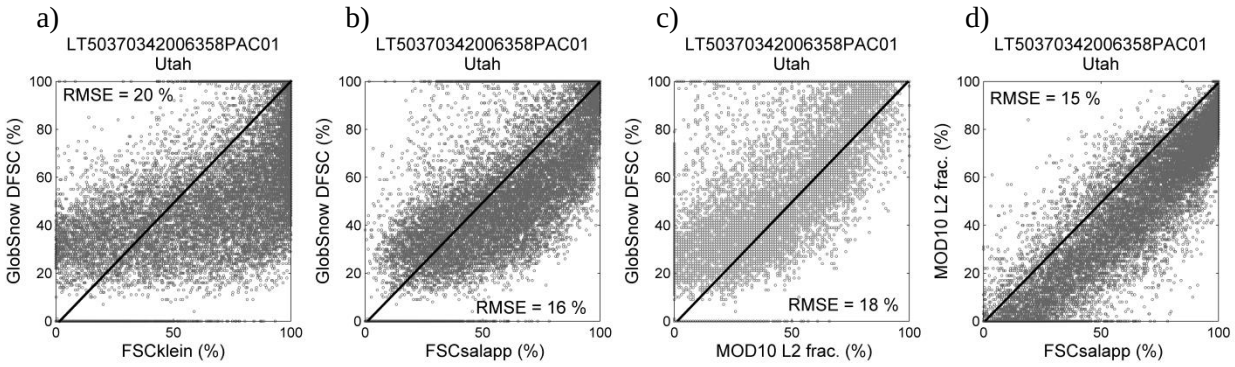


Figure 9. The GlobSnow v2.1 DFSC compared with fractional snow provided by a) FSCklein, b) FSCsalapp, c) MOD10_L2, for TM scene area LT5037342006358PAC01 over Utah, US, on December 24, 2006. d) MOD10_L2 and FSCsalapp for the same scene area.

Case study #4: very dense forest canopy

Forest canopy partly masks the view from satellite sensor to the ground, which typically leads to inaccuracies in fractional snow cover estimation. In GlobSnow SE products, the canopy obscurance is compensated for through SCAmod, but evaluation of the success of the methodology is somewhat difficult due to the lack of appropriate reference data. The TM/ETM+ -based methods described above are not very suitable for forested areas. The Klein method basically identifies the snow in forest through the NDSI-thresholding, but overestimates the moderate to high snow fractions while underestimating or even missing the low snow fractions. The Salomonson and Appel method responds better to the different fractions through linear regression but leads to underestimation as a snow-covered forest provides a lower NDSI than a snow-covered non-forest area.

Here we demonstrate the performance of FSCklein and FSCsalapp for ETM+ scene LE71860172003074SGS00 over the Finnish-Russian border on March 15, 2003, Fig. 10a. From Finnish *in situ* observations at several weather stations and from general climatology we know that the scene area is fully snow-covered. The area is characterized by numerous lakes (ice covered at the time of the image acquisition) and by dense to very dense boreal forests (the latter indicated by the bluish area across the scene from the north-east corner towards the south-west). Since the very dense forests even with under-canopy snow have ETM+ band 2 reflectance below 10%, the reflectance thresholding applied in the provision of FSCklein and FSCsalapp results in FSC=0 for many of the forest pixels. So it is evident that the reflectance thresholding is not reasonable for the densest forests. As expected, FSCklein (Fig. 10c) succeeds relatively well in identifying full snow cover, except for the densest forest (yet underestimating, average scene FSC is 88%), while FSCsalapp (Fig. 10d) results in slight underestimations all over the scene (average scene FSC is 74%). Hence, in this case we can consider FSCklein to better represent the 'truth'.

The GlobSnow DFSC, from the previous date as no concurrent AATSR acquisition was available, performs well with an average scene FSC of 99%, see Fig. 10b. However, the RMSE's gained from pixel-to-pixel comparison with FSCklein and FSCsalapp are as high as 21% and 31%, respectively. This analysis indicates that for densely forested areas, neither of the TM/ETM+ -based methods can provide a reliable reference, and statistical metrics like the RMSE or correlation coefficient are only suggestive.

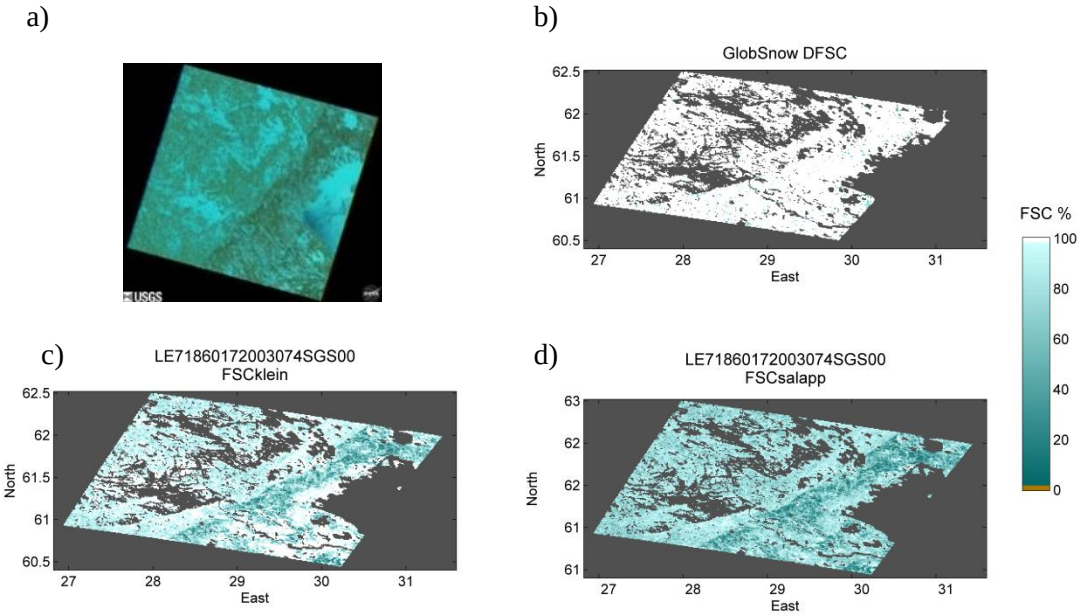


Figure 10. a) ETM+ scene LE71860172003074SGS00, March15, 2003, over the Finnish-Russian borderline with dense forests, full snow cover prevailing, b) the GlobSnow DFSC, c) FSCklein, d) FSCsalapp. The dark grey color indicates no-data (outside image acquisition or water pixels).

From the above results, one might deduce that the Klein method would be preferred over the Salomonson and Appel method for generating the reference FSC for forests. However the result only concerns forests with full snow cover. For fractional snow, the Klein method tends to overestimate, except for low snow fractions for which it tends to underestimate. The level of FSC at which snow overestimation turns into underestimation varies according to forest density i.e. scene to scene but is clearly below 50% according to Rittger et al., (2013). So the Klein method would be reasonable only to identify the presence of snow in forests, not the snow fraction. As the Salomonson and Appel method is capable of detecting snow in forests as well (although underestimating), it could be recommended in general, particularly as it seems work better for open areas.

6. Conclusions

This paper introduces the Snow Extent (SE) product portfolio provided within thr ESA DUE GlobSnow, with special focus on the Daily Fractional Snow Cover (DFSC) of the SE version 2.0 released in 2013 and its successor version 2.1 released in 2014. The SE products include hemispheric daily, weekly and monthly maps of Fractional snow cover derived from ERS-2/ATSR-2 and Envisat/AATSR data, spanning 17 years (1995–2012). The fractional snow cover retrieval is based on the SCAmod method relying on a semi-empirical reflectance model. The model parameterization is the key issue for the performance of the method; therefore, the generation of each parameter is summarily described. The method applied in cloud screening is also introduced, with some considerations concerning on its general performance but without going into details.

The first evaluations of GlobSnow DFSC are presented along with considerations concerning future validations, including the discussion of issues already noticed. The evaluation experiment is accomplished by comparing the DFSC to high-resolution data-based reference FSC. Actual validation

760 is not presented; instead, the feasiblity of two methods for generating the reference FSC from Landsat
761 TM/ETM+ data are investigated for different landcovers, with a particular interest in forested areas.
762 Methods by Klein et al. (1998) and Salomonson and Appel (2006) were tested for five Landsat scene
763 areas. It was concluded that for forests, validation against TM/ETM+ -derived FSC is very easily
764 distorted by the non-representativeness of these reference data. Accordingly, validation results for
765 heavily forested areas can only be suggestive. For sparsely forested and non-forested areas, the
766 fractional snow retrieval methodology by Salomonson and Appel (2006) was found to be more
767 feasible. A likely case of applying a value too low for one of the SCAmod parameters (snow-free
768 ground reflectance) is identified in the US intermontane plateau area. This is well distinguished as
769 overestimated low snow fractions in the DFSC. Some overestimations in very dense forests are also
770 expected, due to the narrow dynamics of reflectance observed from forests, either snow-free or snow-
771 covered. Overall, these first evaluations suggest that GlobSnow SE products give a good performance
772 for forested areas but this is necessarily not shown in validation due to the non-representativeness of
773 the reference data.

774 For two of the scenes investigated, MODIS Collection 5 MOD10_L2 fractional product was also
775 presented and compared with reference data and the GlobSnow DFSC. The analysis of a forested
776 scene indicated that the temperature screening applied in the MOD10_L2 provision would lead to
777 false snow omissions which were not present in the GlobSnow DFSC due to the more liberal
778 temperature screening applied. This also emphasises the advantage of the exclusion of temperature
779 screening in the MODIS Collection 6 snow products. Moreover, snow/cloud confusion present in
780 MOD10_L2 was not identified in the GlobSnow DFSC in the two scenes investigated. However these
781 results are based on limited data; more investigations on the performance of the cloud screening as
782 well as temperature thresholding will be conducted in the future.

783 The results and considerations presented in this paper will be reflected in upcoming studies. There
784 is extensive validation and evaluation work going on within the GlobSnow-2 project, aiming at
785 publication in 2015. The GlobSnow v2.1 SE product is also one of the data sets investigated in the
786 ESA funded project SnowPEX (2014–2016, ESA Contract No. 4000111278/14/I/LG), where

hemispheric-scale evaluation and intercomparison of several Earth observation-based snow products will be carried out.

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990

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

993

994 Figure 2. Snow-free ground reflectance maps applied in the GlobSnow v2.0 and v2.1 SE production:
995 North America (*Left*) and Eurasia (*Right*).

996

997 Figure 3. Map of the apparent two-way forest transmissivity map (t^2) for North America (*Left*) and for
998 Eurasia (*Right*).

999

1000 Figure 4. Uncertainty layer for v2.1 SE Monthly product, April 2006. Statistical error (non-biased
1001 standard error) for each FSC estimate is provided in FSC %-units. A yellow color indicates cloudy
1002 areas, cyan indicates non-classified areas of permanent snow and ice (see class 'Glacier' in Fig. 1),
1003 according to the GlobCover data.

1004

1005 Figure 5. SCDA2.0 cloud scheme used in GlobSnow v2.0 and v2.1 SE production.

1006

1007 Figure 6. FSC at 0.01º pixel size, for Landsat TM scene area LT51910132006125KIS00, Northern
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1011 GlobSnow DFSC, f) FSCklein, g) MOD10_L2 fractional product, the yellow color indicates clouds.

1012

1013 Figure 7. Comparison between the GlobSnow DFSC and two methods for FSC retrieval from
1014 TM/ETM+ data over Kazakhstan (top pane) and Nunavut, Canada (bottom pane). *Left*: Browse
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Figure 8. Fractional snow cover maps as provided by a) FSCklein, b) FSCsalapp, c) the GlobSnow DFSC, d) MOD10_L2, for TM scene LT5037342006358PAC01 over Utah, US, on December 24, 2006 (e). The yellow color corresponds to clouds.

Figure 9. The GlobSnow v2.1 DFSC compared with fractional snow provided by a) FSCklein, b) FSCsalapp, c) MOD10_L2, for TM scene area LT5037342006358PAC01 over Utah, US, on December 24, 2006. d) MOD10_L2 and FSCsalapp for the same scene area.

Figure 10. a) ETM+ scene LE71860172003074SGS00, March15, 2003, over the Finnish-Russian borderline with dense forests, full snow cover prevailing, b) the GlobSnow DFSC, c) FSCklein, d) FSCsalapp. The dark grey color indicates no-data (outside image acquisition or water pixels).