ESA Climate Change Initiative CCI+

Product User Guide

snow cci

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ESA STUDY CONTRACT REPORT

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4000124098/18/I-NB	Product User Guide		ENVEO
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Abstract:

The European Space Agency (ESA) Climate Change Initiative aims to generate high quality Essential Climate Variables (ECVs) derived from long-term satellite data records to meet the needs of climate research and monitoring activities. The main goal of *snow_cci* project is to generate homogeneous, well-calibrated, long-term time series of the key snow cover variables snow area extent and snow mass for climate applications.

This document is a user guide for the snow products produced in the second iteration of the *snow_cci* project. The product time series are snow cover fraction (SCF, viewable and on the ground) based on the sensors MODIS, AVHRR, ATSR-2/AATSR and SLSTR (separate time series) and snow water equivalent (SWE) based on the sensors SMMR, SSM/I and SSMIS (one combined time series). The document provides a comprehensive description of the thematic content of the products, coding, metadata and file format. It also includes a description of known limitations and strengths of the products. Guidelines for product access and suggestions for software tools to handle the data, are also provided.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

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1.0	11 / 11 / 2019	First version approved by ESA	Schwaizer, G.
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1. INTRODUCTION

The European Space Agency (ESA) Climate Change Initiative aims to generate high quality Essential Climate Variables (ECVs) derived from long-term satellite data records to meet the needs of climate research and monitoring activities, including the detection of variability and trends, climate modelling, and aspects of hydrology and meteorology. The main goal of the *snow_cci* project is to generate homogeneous, well-calibrated, long-term time series of the key snow cover variables snow area extent and snow mass for climate applications.

1.1. Scope of the Document

This document is a user guide for the snow products produced in the second iteration of the *snow_cci* project. The product time series are snow cover fraction (SCF, viewable and on the ground) based on the sensors Moderate resolution Imaging Spectroradiometer (MODIS), Advanced Very High Resolution Radiometer (AVHRR), Along-Track Scanning Radiometer (ATSR-2) and Advanced Along-Track Scanning Radiometer (AATSR) (separate time series) and snow water equivalent (SWE) based on the sensors Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager / Sounder (SSMIS) (one combined time series). The document provides a comprehensive description of the thematic content of the products, the coding, metadata and file format. It also includes a description of known limitations and strengths of the products. Guidelines for product access and suggestions for software tools to handle the data, are also provided.

1.2. Document Structure

The document introduces with a summary description of the *snow_cci* project (Chapter 2). Then follows documentation on the snow cover fraction (SCF) products (Chapter 3), including a general description of the snow variable in the context of this project (Section 3.1) followed by a specific description of the MODIS SCF product (Section 3.2), AVHRR SCF product (Section 3.3), and the plans for the SCF retrieval from the sensors ATSR-2/AATSR (Section 3.4) and Sea and Land Surface Temperature Radiometer (SLSTR) (Section 3.5). The snow water equivalent (SWE) product is then described in Chapter 4. All product descriptions include subsections for thematic information, overall product characteristics, data representation and known strengths and limitations. Then follows a description that deals with topics common to all the products (Chapter 5). These are filename convention, file format – including global and variable attributes, and metadata – and at last software tools to handle the products and how to access the products, including our use and citing policy.

1.3. Applicable and Reference Documents

[AD-1] Phase 1 of the ESA Climate Change Initiative CCI+ New ECVS (Snow). ESRIN Contract No: 4000124098/18/I-NB.

[AD-2] Climate Change Initiative Extension (CCI+) Phase 1 – New Essential Climate Variables (Annex E: Snow ECV (Snow_cci), ESA-CCI-PRGM-EOPS-SW-17-0032.

[AD-3] Technical Proposal (Part 3) in response to ESA Climate Change Initiative Phase 1 ESA ITT AO/1-9041/17/I-NB, ENVEO Innsbruck, Austria.

[RD-1] Wunderle, S., Naegeli, K., Schwaizer, G., Nagler, T., Marin, C., Notarnicola, C., Derksen, C., Luojus, K., Metsämäki, S., Solberg, R. (2018). ESA CCI+ Snow ECV: Data Access Requirements Document.

[RD-2] Notarnicola, C., Marin, C., Schwaizer, G., Nagler, T., Luojus, K., Derksen, C., Mortimer, C., Wunderle, S., Nägeli, K. (2019). ESA CCI+ Snow ECV: Product Validation Plan, version 1.0, August 2019.

[RD-3] Wiesmann A., Hetzenecker M., Schwaizer G., Nagler T., Takala M., Luojus K. (2019) ESA CCI+ Snow ECV: System Requirements Document, version 1.0, March 2019.

[RD-4] Solberg, R., G. Schwaizer, T. Nagler, M. Hetzenecker, S. Wunderle, K. Naegeli, C. Neuhaus, A. Wiesmann, K. Luojus, M. Takala, J. Pulliainen, J. Lemmetyinen, and M. Moisander (2020) ESA CCI+ Snow ECV: Climate Research Data Package, version 2.0, October 2020.

[RD-5] Salberg, A.-B., K. Luojus, C. Derksen, C. Marin, R. Solberg, L. Keuris, G. Schwaizer, T. Nagler, (2020) ESA CCI+ Snow ECV: End-to-End ECV Uncertainty Budget, version 2.0, October 2020.

1.4. Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
ATSR-2	Along-Track Scanning Radiometer
AMSR	Advanced Microwave Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CCI	Climate Change Initiative
CEDA	Centre for Environmental Data Analysis
DEM	Digital Elevation Model
DMSP	Defence Meteorological Satellite Program
CP	Contractual Phase
DARD	Data Access Requirement Document
ECV	Essential Climate Variable
ESA	European Space Agency
GAC	Global Area Coverage

GCMD	Global Change Master Directory
MetOp	European Meteorological Operational Satellite
MODIS	Moderate resolution Imaging Spectroradiometer
NDSI	Normalized Difference Snow Index
NOAA	National Oceanic and Atmospheric Administration
PMR	Passive Microwave Radiometer
PVP	Product Validation Plan
QA4EO	Quality Assurance framework for Earth Observation
RMSE	Root Mean Square Error
SCF	Snow Cover Fraction
SCFG	Snow Cover Fraction, snow on the Ground
SCFV	Snow Cover Fraction, Viewable snow
SLSTR	Sea and Land Surface Temperature Radiometer
SMMR	Scanning Multichannel Microwave Radiometer
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager / Sounder
SWE	Snow Water Equivalent
UTC	Coordinated Universal Time
WGS	World Geodetic System

2. *SNOW_CCI* PROJECT

Seasonal snow cover is the largest single component of the cryosphere, covering about 50% of the Northern Hemisphere's land surface during mid-winter. The seasonal snow cover is an important component of Earth's hydrological and climate systems.

The seasonal snow cover is a crucial and challenging research issue in climate analysis and modelling. It influences energy, moisture and gas fluxes between the land surface and the atmosphere; its high albedo provides a significant feedback effect in a warming climate; and its sensitivity to precipitation and temperature regimes makes it widely recognised as a fundamental indicator of climate variability and change. Snow is also a major, if not dominant, freshwater source in many alpine, high- and mid-latitude regions and an important contribution to the global water cycle.

The European Space Agency (ESA) Climate Change Initiative aims to generate high quality Essential Climate Variables (ECVs) derived from long-term satellite data records to meet the needs of climate research and monitoring activities, including the detection of variability and trends, climate modelling, and aspects of hydrology and meteorology. The main goal of the *snow_cci* project is to generate homogeneous, well-calibrated, long-term global time series of daily products of the key snow cover variables snow cover fraction (SCF) from optical sensor satellite data and snow water equivalent (SWE) from passive microwave radiometer satellite data. This includes to set up reliable, fully validated processing chains for these products and carrying out a comprehensive validation/inter-comparison study.

The *snow_cci* project focuses in its first phase on the development and implementation of methods and processing systems to generate consistent multi-sensor time series from ESA and third-party satellites. These products are contributing to the determination of the long-term trends in seasonal snow since beginning of the early 1980s, currently still a matter of debate due to various inconsistencies between different snow cover data sets, as shown in the ESA QA4EO project SnowPEx.

The SCF product has a spatial resolution ranging between 0.01° and 0.05° (about 1 km and 5 km, respectively, at mid-latitudes). The aim is to generate time series of daily global homogeneous snow cover fraction maps from different optical satellite sensors. In forested areas, information is provided for snow on the top of the forest canopy (SCFV, "viewable snow") and for snow on the ground applying a canopy correction (SCFG, "snow on ground"). The products are expressed as fractional snow per pixel and are derived from medium spatial resolution optical satellite data. The multi-sensor time series, starting from the beginning of the 1980s to present day, include data from AVHRR-2/3, ATSR-2, AATSR, MODIS, Sentinel-3A/B SLSTR and Spot/Proba-V Vegetation. For each product, the uncertainty is estimated for each pixel taking spectral capabilities, calibration, and geolocation accuracy into account. A key aspect of the long time series of daily products is cross-sensor consistency of the products.

The snow water equivalent production system is built on the GlobSnow SWE production system and is further developed by improving various aspects of the processing chain, including time-varying snow density, influence of land cover and implementation of techniques for enhancement of brightness temperature resolution. The daily global time series is based on SMMR and SSM/I data (from several DMSP F-series satellites) starting in 1979 to present day. A key aspect is the synergy between the daily time series of SCF and SWE products, with the aim to get a consistent cross-parameter data set.

The first version of the climate data record generated in the frame of the *snow_cci* project is based on MODIS and AVHRR sensors for SCF (two separate time series) and on SMMR and SSM/I for SWE (combined in one time series). As ESA is reprocessing ATSR-2, AATSR and SLSTR data, the corresponding snow products are delayed. The first reprocessed AATSR data were available mid-September 2020, and the full Level 1B time series is planned to be completed by the end of 2020. SCF products from AATSR are planned to be provided in early February 2021. The timing for ATSR-2 and SLSTR based SCF products depend on data availability, which is not yet clear. Table 2.1 provides an overview of the products sets planned for *snow_cci*.

Table 2.1: Input data time series processing plan per project year.

Product	*Project Year 1*	*Project Year 2*	*Project Year 3*
SCF	AVHRR/2 (1982-2016) AVHRR/3 (2006-2018) MODIS (Terra only; 2000-2018)	AVHRR/2 (1982-2016) AVHRR/3 (2006-2019) MODIS (2000-2019) ATSR-2 (1995-2003; samples) AATSR (2002-2013; samples) SLSTR (2016-2019; samples) Merged AVHRR (1982-2019) Merged ATSR-2, AATSR & SLSTR (1995-2019) Merged Terra and Aqua MODIS (2000-2019) Merged all missions (1981-2019)	AVHRR/2 (1982-2016) AVHRR/3 (2006-2020) ATSR-2 (1995-2003) AATSR (2002-2013) MODIS (2000-2020) SLSTR (2016-2020) Merged AVHRR (1982-2020) Merged ATSR-2, AATSR & SLSTR (1995-2020) Merged Terra and Aqua MODIS (2000-2020) Merged all missions (1981-2020)
SWE	SMMR (1979-1987) SSM/I, SSMIS (1987-2018)	SMMR (1979-1987) SSM/I, SSMIS (1987-2019) Merged all missions (1979-2019)	SMMR (1979-1987) SSM/I, SSMIS (1987-2020) Merged all missions (1979-2020)

3. SNOW COVER FRACTION

3.1. Thematic Description

The *snow_cci* SCF products are derived from medium resolution optical data (see Table 2.1), and contains two separate variables: (i) the snow cover at the surface in open areas and on top of vegetation cover that is present, such as forest canopies (called 'viewable snow') and (ii) snow extent on ground for open land (same as 'viewable snow') and corrected for masking by trees in forested areas (called 'snow on ground'). The fractional snow cover per grid cell of the sensor is provided as a percentage.

Two baseline candidate algorithms are selected for the development of SCF products: the Normalized Difference Snow Index (NDSI)-based method developed originally for MODIS, which provides in forested areas viewable snow (Salomonson and Appel, 2006), and the SCAmod algorithm with heritage to the ESA GlobSnow project which provides in forested areas snow on ground (Metsämäki et al., 2015). The algorithms were selected because they ranked highly within SnowPEx project's studies. The SCAmod algorithm is selected and adapted for the SCF version 1.0 retrieval using auxiliary data newly developed in the *snow_cci* project for a consistent detection of viewable snow and the snow on ground. The SCF processing chain has four main modules: pre-processing of satellite data, cloud screening, pre-classification of snow-free areas based on the NDSI and SCF retrieval using the adapted SCAmod.

The SCF product provides the fraction of the observed area corresponding to a pixel covered by snow, given as percentage. The products include pairs of files providing SCF for viewable snow and snow on ground, both including a measure of retrieval uncertainty per pixel as a separate layer. SCF is calculated only for cloud-free land areas; open water areas (inland and oceans) as well as glaciers and ice sheets are masked using a common land mask. For Greenland, coastal areas (with no land ice) are included. Coastal ice-free areas of Antarctica and islands in the Southern Ocean are excluded in the version 1.0 but might be considered for future versions if requested by users. Permanent ice and open water areas are treated as static masks. Pixels acquired at large solar zenith angles (sza) are masked as class (polar) night.

Two time series of SCF are processed, with the spatial resolution depending on the input optical imagery: 0.05° from 1982 to 2019 (based on AVHRR) and 0.01° from 2000 to 2019 (based on MODIS). No temporal aggregation of the products is included in the version 1.0.

3.2. MODIS SCF

3.2.1. Overall Description

The MODIS based *snow_cci* SCF product time series covers the period 2000-2019. Global SCF products are available at daily temporal resolution with cloud-cover flagged. The product is based on data from the MODIS sensor aboard the Terra satellite (launched 1999). The sensor provides data in 250, 500 and 1000 m spatial resolution. 1 km data is provided from all 36 spectral bands.

The whole global Terra MODIS 1 km Level 1B data set was downloaded and made available to the project at NR. It was decided not to fill in gaps with Aqua MODIS data in the version 1.0 as potential impacts from illumination variations due to the afternoon orbit have not yet been analysed properly.

The characteristics of the MODIS SCF product version 1.0 is described in Table 3.1.

Table 3.1: MODIS SCF products version 1.0. These characteristics are valid for the viewable snow cover fraction (SCFV) and the snow cover fraction on ground (SCFG) products.

Subject	*Snow Cover Fraction*
Variable	Snow cover fraction [%]
Accuracy target	10-20% unbiased RMSE
Retrieval algorithm	SCAmod, Metsämäki et al., 2015, adapted and improved
Uncertainty algorithm	Error propagation, adapted from Salminen et al. (2018)
Cloud screening algorithm	Simple Cloud Detection Algorithm, Metsämäki et al., 2015, adapted and improved
Satellite(s)	Terra (NASA)
Sensor(s)	MODIS
Input product(s)	MOD02 and MOD03 Collection 6.1
Geographical domain(s)	Global
Start date time series	25.02.2000
End date time series	31.12.2019
Grid size	0.01°
Projection/datum	Geographical (lat/lon)/WGS 84
Temporal resolution	Daily
Temporal aggregation	None
Number of layers	2
Metadata	Global attributes in NetCDF4 file, CF-v1.8, conformal with CCI data standards v2.2, 19/05/2020
Auxiliary data	Water and permanent snow and ice masks aggregated from Land Cover CCI product for the year 2000; forest canopy transmissivity map for the retrieval of snow on ground, reflectance maps for snow free forest and snow free ground
Data representation	Unsigned byte (8 bits)
File format	NetCDF4, CF-v1.8
Product access	CCI Data Portal, CEDA archive: SCFV products: https://catalogue.ceda.ac.uk/uuid/ef8eb5ff84994f2ca416dbb2df7f72c7 SCFG products: https://catalogue.ceda.ac.uk/uuid/3b3fd2daf3d34c1bb4a09efeaf3b8ea9

3.2.2. Data Representation

The products are provided as two files, each containing two layers:

1. SCFV product:
    a. Snow cover fraction, viewable snow
    b. Uncertainty estimate for snow cover fraction, viewable snow
2. SCFG:
    a. Snow cover fraction, snow on the ground
    b. Uncertainty estimate for snow cover fraction, snow on the ground

The coding of the product and the associated uncertainty estimation is described in Table 3.2 and Table 3.3, respectively. Examples of the MODIS-based SCFV and SCFG products are shown in Figure 3.1 and Figure 3.3, the associated uncertainty estimations per pixel are presented in Figure 3.2 and Figure 3.4, respectively.

Table 3.2: Coding for the MODIS SCF products (valid for viewable snow and snow on ground).

Code(s)	Description
0-100	SCF [%]; 0 = snow free; 100 = fully snow covered
205	Cloud
206	(Polar) Night (satellite data available, but large solar zenith angle (sza > 83°) does not allow classification)
210	Water
215	Glaciers, icecaps, ice sheets
252	ERROR: Retrieval failed
253	ERROR: Input data error (e.g. bad pixels)
254	ERROR: No satellite acquisition
255	Not valid data
All other values	Not used

Table 3.3: Coding for the MODIS SCF uncertainty layer (RMSE estimate), valid for uncertainty estimation of SCFG and SCFV.

Code(s)	Description
0	Uncertainty for pixels classified as definitely snow free in the NDSI-based pre-classification
1-100	Unbiased RMSE for pixels considered in the SCF retrieval, resulting in snow cover fraction in percent (0 = snow free; 100 = fully snow covered in SCF product). For snow-free pixels resulting from the SCF retrieval approach, also the uncertainty estimation is provided.
205	Cloud (snow retrieval not possible due to masking of earth surface, no uncertainty estimate provided.)
206	(Polar) Night (satellite data available, but large solar zenith angle (sza > 83°) does not allow classification)
210	Water
215	Glaciers, ice caps, ice sheets
252	ERROR Code: Retrieval / Classification failed
253	ERROR Code: Input data error (e.g. bad pixels, etc)
254	ERROR Code: No satellite data value
255	Not Valid Pixel
All other values	Not used

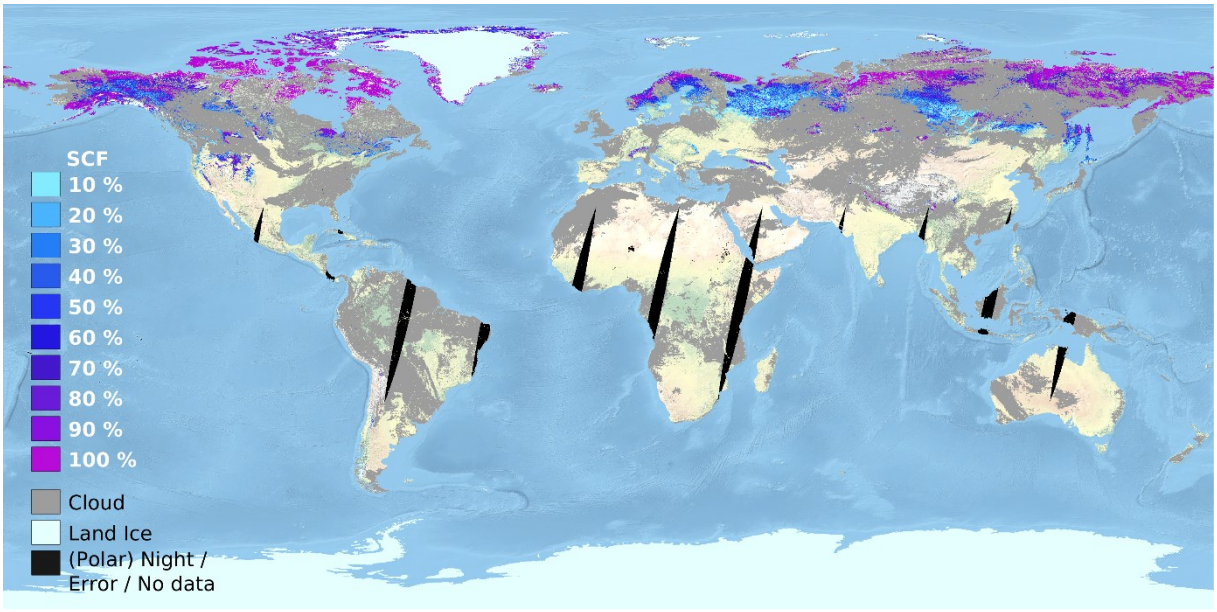

Figure 3.1: SCFV product example from Terra MODIS on 31 March 2002.

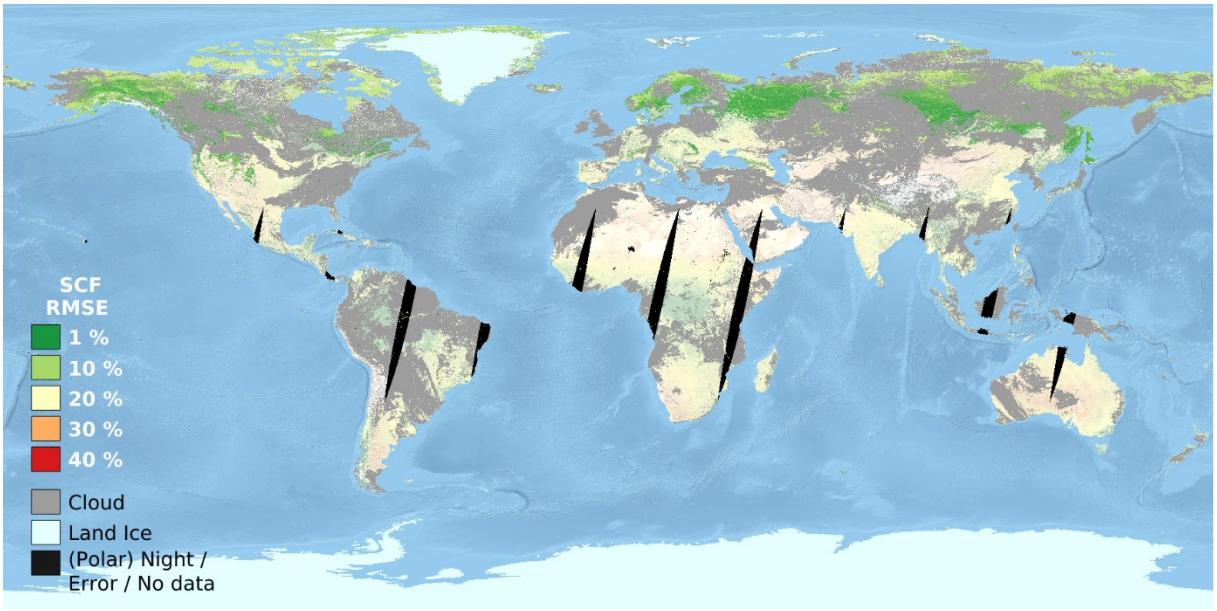

Figure 3.2: Example of the uncertainty estimation for the SCFV product from MODIS data on 31 March 2002 (cf. Figure 3.1).

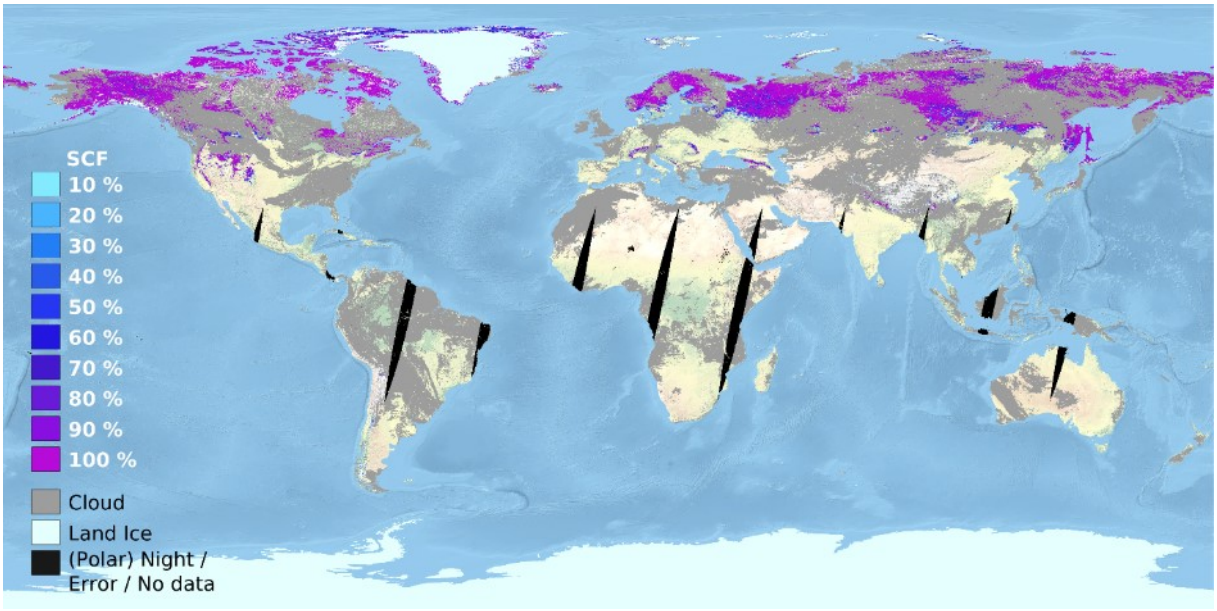

Figure 3.3: SCFG product example from Terra MODIS on 31 March 2002.

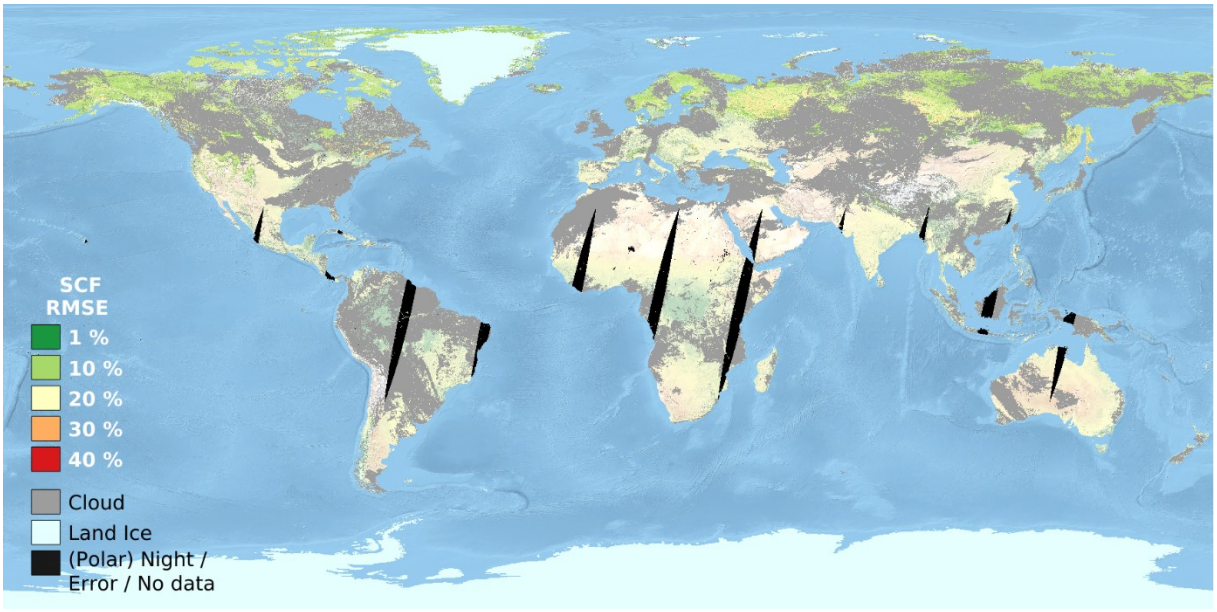

Figure 3.4: Example of the uncertainty estimation for the SCFG product from MODIS data on 31 March 2002 (cf. Figure 3.3).

3.2.3. Known Strengths and Limitations

Strengths: The products provide the fraction of snow cover per pixel on global land areas. The spatial resolution of the products with 0.01° pixel spacing is high compared to other available satellite-based global snow products. In forested areas, the SCFV products provide information on snow on the top of the forest canopy, while the SCFG products provide the canopy-corrected snow on ground. The snow classification in open land for SCFV and SCFG is consistent for the product generation from Terra MODIS data for the full time series, from end of February 2000 till December 2019. The applied pre-classification to identify pixels with high probability of snow-free conditions, e.g. in very warm regions, improves the global snow extent product significantly. The cloud-screening approach is developed for clouds over snow and works in general better than other cloud masks.

Limitations: Changes in the forest due to forest clearance or reforestation are not yet considered, but a static forest mask valid for the year 2000 is used to separate between open land and forested areas. The classification accuracy of pixels affected by cloud shadow or in small cloud gaps is often lower than for large areas observed at clear-sky conditions. Further improvements of the cloud screening approach are currently in development. Pixels with a solar zenith angle greater than 83° are too dark for a reliable classification and are masked as night or polar night. Although the major water bodies are masked out, misclassification of snow can occur for changing water bodies, as a static mask from the year 2000 is used for identifying water for the full time series.

3.3. AVHRR SCF

3.3.1. Overall Description

The AVHRR SCF product time series cover the period 1982-2019. Global SCF products are available at daily temporal resolution with cloud cover flagged. The Cloud CCI project's cloud mask is used for cloud masking.

The Advanced Very High Resolution Radiometer (AVHRR) is one of the oldest systems in orbit (since 1981), born by NOAA satellite platforms and recently also on the European MetOp satellites. AVHRR is the only sensor offering an exceptional long optical data record (almost 40 years) for global applications, with a spatial resolution of 4 km (Global Area Coverage, GAC). Only local archives offer data with 1 km spatial resolution (Local Area Coverage, LAC) for shorter periods and regionally limited.

The AVHRR sensors had two major changes over the lifetime of its programme. The AVHRR-1 aboard NOAA-8 and -10 duplicated the thermal band 4. Therefore, this sensor is not used for snow monitoring because the capability for cloud detection is limited. The main difference between AVHRR-2 and -3 is splitting of channel 3 into two channels 3A and 3B in AVHRR-3.

This exceptional long data record based on AVHRR was also the driver to use this data set for ESA Cloud CCI project. In advance of the actual cloud retrieval, the AVHRR data were calibrated and geocoded. Therefore, this processed and readily available data set of AVHRR GAC data are also used for the retrieval of the global SCF time series.

The characteristics of the AVHRR SCF product is described in Table 3.4.

Table 3.4: AVHRR SCF version 1.0.

Subject	*Snow Cover Fraction*
Variable	Snow cover fraction [%]
Accuracy target	10-20% unbiased RMSE
Retrieval algorithm	NDSI (Salomonson and Appel, 2006) as precondition for SCAmod (Metsämäki et al., 2015)
Uncertainty algorithm	Salberg et al. 2020 [RD-5]
Cloud screening algorithm	Cloud CCI product; Version 3
Satellite(s)	NOAA
Sensor(s)	AVHRR/2, AVHRR/3
Input product(s)	GAC (PyGAC processed by ESA Cloud CCI consortium)
Geographical domain(s)	Global
Start date time series	01.01.1982
End date time series	31.12.2019
Grid size	0.05°
Projection/datum	Geographical (lat/lon)/WGS 84
Temporal resolution	Daily
Temporal aggregation	None

Subject	Snow Cover Fraction
Number of layers	2
Metadata	Global attributes in NetCDF4 file, CF-v1.9, conformal with CCI data standards v2.2, 19/05/2020
Data representation	Unsigned byte (8 bits)
File format	NetCDF4, CF-v1.9
Product access	CCI Data Portal, CEDA archive: SCFV products: https://catalogue.ceda.ac.uk/uuid/d9df331e346f4a50b18bcf41a64b98c7 SCFG products: https://catalogue.ceda.ac.uk/uuid/5484dc1392bc43c1ace73ba38a22ac56

3.3.2. Data Representation

The products are provided as two files, each containing two layers:

1. SCFV product:
    a. Snow cover fraction, viewable snow
    b. Uncertainty estimate for snow cover fraction, viewable snow
2. SCFG:
    a. Snow cover fraction, snow on the ground
    b. Uncertainty estimate for snow cover fraction, snow on the ground

The product coding is explained in Table 3.5 and Table 3.6. Examples of the AVHRR-based SCF products are shown in Figure 3.5 (SCFV) and Figure 3.7 (SCFG). Examples of corresponding uncertainty are shown in Figure 3.6 (for SCFV) and Figure 3.8 (for SCFG).

Table 3.5: Coding and legend for the AVHRR SCF product, % SCF layer.

Code(s)	Description
0-100	SCF [%]; 0 = snow free; 100 = fully snow covered
205	Cloud masked (including cloud shadow)
206	Satellite data available, but polar night
210	Water
215	Glaciers, icecaps, ice sheets
254	ERROR: No satellite acquisition
All other values	Not used

Table 3.6: Coding and legend for the AVHRR SCF product, uncertainty layer (RMSE estimate).

Code(s)	Description
0-100	Estimate of RMSE [% SCF]
205	Cloud masked (including cloud shadow)
206	Satellite data available, but polar night
210	Water
215	Glaciers, icecaps, ice sheets
254	ERROR: No satellite acquisition
All other values	Not used

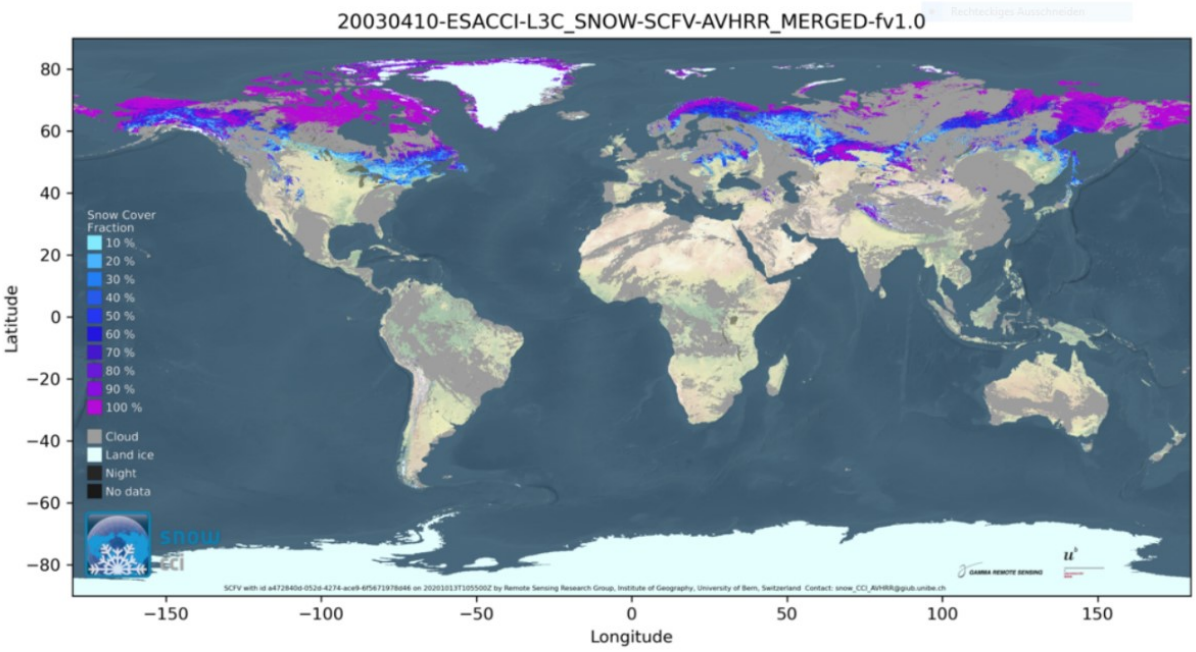

Figure 3.5: Product example on 10 April 2003; snow cover fraction viewable (SCFV).

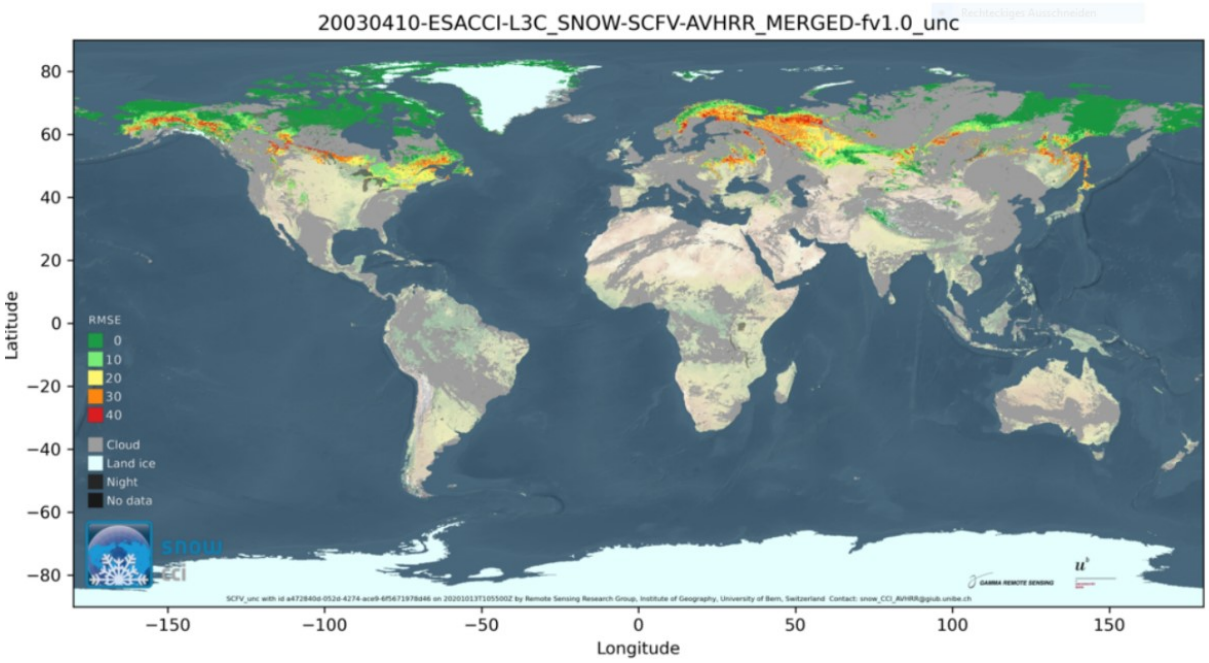

Figure 3.6: Product example on 10 April 2003; uncertainty of SCFV.

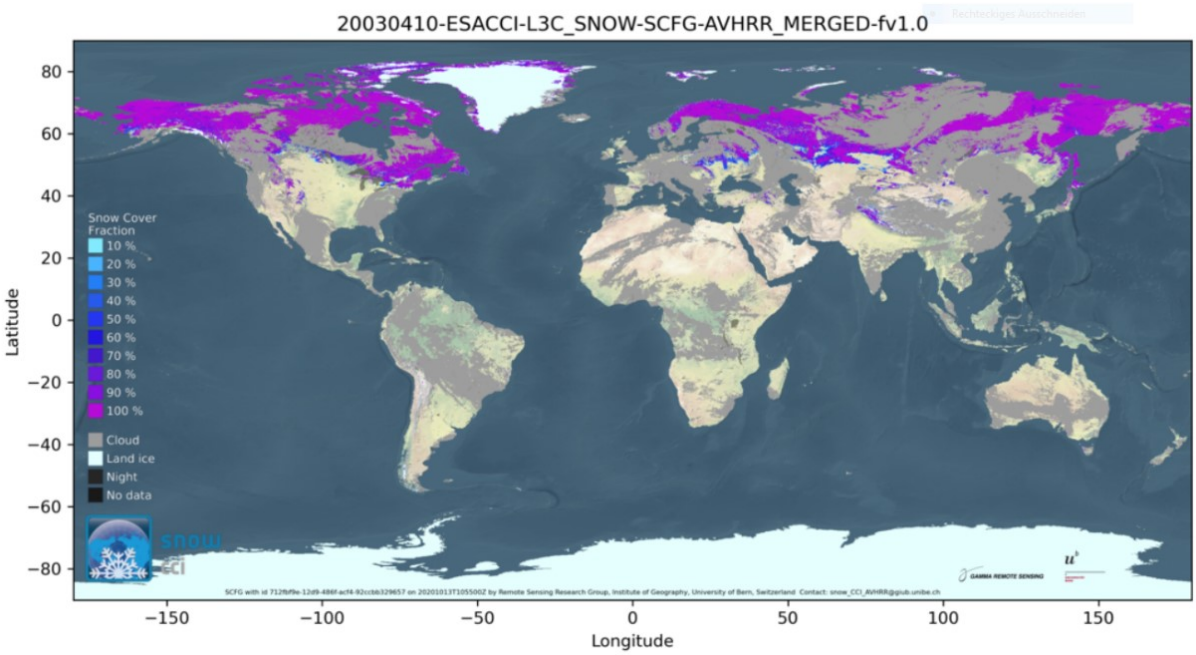

Figure 3.7: Product example on 10 April 2003; snow cover fraction ground (SCFG).

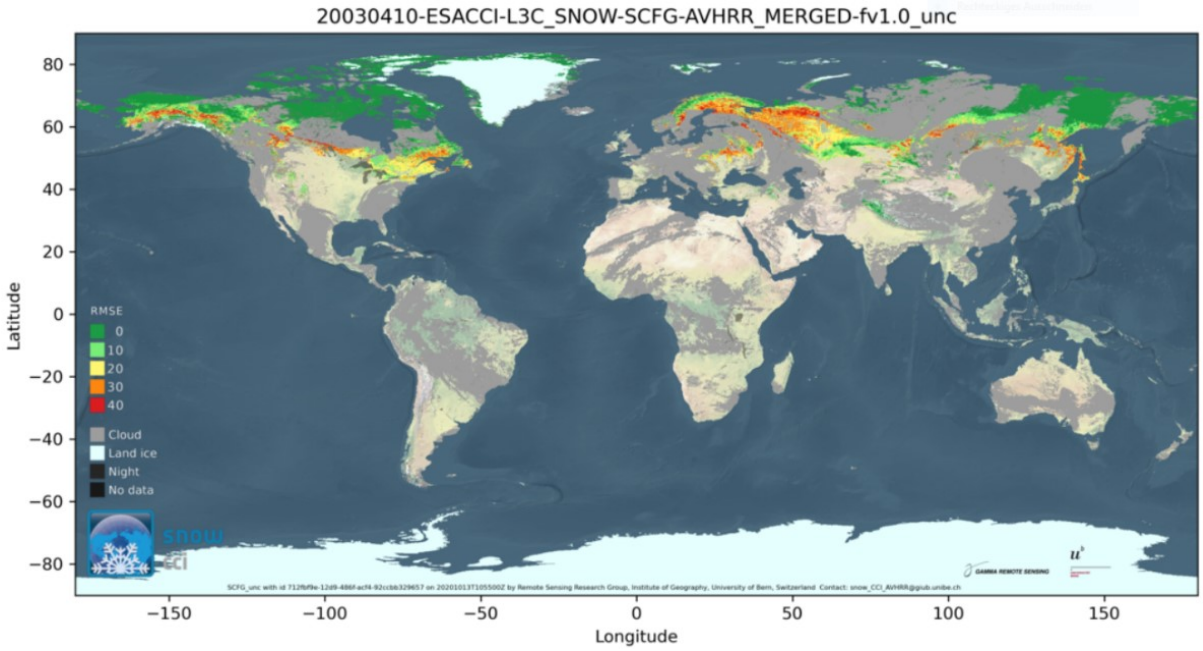

Figure 3.8: Product example on 10 April 2003; uncertainty of SCFG.

3.3.3. Known Strengths and Limitations

Strengths: The only sensor in orbit with a time series of almost 40 years fulfilling the requirements of WMO for climate period; the Cloud CCI's cloud mask is reliable and consistent over time.

Limitations: Medium spatial resolution of 4 km results in reduced detectability of snow in heterogeneous terrain in comparison to 1 km data. Lack of orthorectification may cause radial positional shifts in mountains. Channel 3 of the early AVHRR/2 sensor (NOAA-7, NOAA-9) has some noise, which affects the quality of SCF based on NDSI as precondition for SCAmod.

3.4. ATSR-2/AATSR SCF

Reprocessing of the raw data of these sensors is ongoing at ESA. SCF products are planned to be generated based on these sensors when the reprocessed satellite data are available. Final products will be made available to the public.

The first months of reprocessed Level-1B AATSR data were made available to NR mid-September 2020. All AATSR data is expected to be reprocessed by the end of 2020. The ATSR-2 processor is still under implementation. NR has received a few scenes processed with a lab prototype. Reprocessing is expected to take place in spring 2021.

3.5. SLSTR SCF

Reprocessing of the raw data of this sensor is ongoing at ESA. SCF products are planned to be generated based on this sensor when the reprocessed satellite data are available. Final products will be made available to the public.

4. SNOW WATER EQUIVALENT

4.1. Thematic Description

Snow water equivalent (SWE) is an important variable indicating the amount of accumulated snow on land surfaces. The retrieval is based on passive microwave radiometer (PMR) data considering the change of brightness temperature due to different snow depth, snow density, grain size and more. The retrieval algorithm handles data from the sensors SMMR, SSM/I, SSMIS, AMSR-E and AMSR-2. Between AMSR-E and AMSR-2 there is a gap between October 2011 and July 2012, but the data set has low priority for the generation of the global time series.

The *snow_cci* SWE product is based on the ESA GlobSnow SWE retrieval approach (Takala et al. 2011). The retrieval methodology combines satellite passive microwave radiometer (PMR) measurements with ground-based synoptic weather station observations by Bayesian non-linear iterative assimilation. A background snow-depth field from re-gridded surface snow-depth observations and a passive microwave emission model are required components of the retrieval scheme. Improvements to the GlobSnow algorithm implemented for *snow_cci* version 1 include the utilisation of an advanced emission model with an improved forest transmissivity module and treatment of sub-grid lake ice. Because of the importance of the weather station snow-depth observations on the SWE retrieval, there is improved screening for consistency through the time series.

Version 1 of the *snow_cci* SWE product is based on SMMR, SSM/I and SSMIS PMR data for non-alpine regions of the Northern Hemisphere. Because of known limitations in alpine terrain, a complex-terrain mask is applied based on the sub-grid variability in elevation determined from a high-resolution digital elevation model. All land ice and water bodies are also masked; retrievals are not produced for coastal regions of Greenland.

Future extension of the SWE product to the Southern Hemisphere is dependent on sufficient in situ snow-depth measurements for algorithm input, whether extensive snow-covered land occurs outside of the alpine mask and the availability of snow-course measurements for validation. These issues will be investigated for later product versions.

4.2. Overall Product Description

The *snow_cci* SWE product time series v1.0 covers the period 1979-2018. Northern Hemisphere SWE products are available at daily temporal resolution with alpine areas masked. The product is based on data from the SMMR aboard NIMBUS-7, and SSM/I and SSMIS sensors aboard DMSP 5D F-series satellites. The satellite bands provide spatial resolutions between 15 and 69 km, and are re-gridded to 25 km pixel spacing.

SWE products over the full Northern Hemisphere are produced daily for the period 1988 – 2018, and bi-daily for the period 1979 – 1987.

The characteristics of the SWE product version 1.0 is described in Table 4.1.

Table 4.1: *snow_cci* SWE version 1.0 specifications.

Subject	*Description*
Variable	Snow water equivalent [mm]
Accuracy target	20-30% unbiased RMSE
Retrieval algorithm	Takala et al., 2011; Pulliainen, 2006
Masking	Mountainous areas, glaciers/permanent ice
Satellite(s)	Nimbus-7; DMSP 5D F8, F11, F13, F17
Sensor(s)	SMMR, SSM/I and SSMIS
Input product(s)	Calibrated brightness temperatures for 19 & 37 GHz bands for SMMR, SSM/I, SSMIS from NSIDC
Geographical domain(s)	Northern Hemisphere
Start date time series	6 January 1979
End date time series	31 May 2018
Grid size	0.25°
Projection/datum	Geographical (lat/lon)/WGS 84
Temporal resolution	Daily
Temporal aggregation	None
Number of SWE data layers	2
Metadata	Global attributes in NetCDF4 file, CF-v1.7, conformal with CCI data standards v2.1, 2019
Data representation	Signed short (16 bits)
File format	NetCDF4, CF-v1.7
Product access	CCI data portal, CEDA archive: https://catalogue.ceda.ac.uk/uuid/fa20aaa2060e40cabf5fedce7a9716d0

4.3. Data Representation

The SWE product includes two data layers:

1. SWE: Snow water equivalent retrieval
2. SWE_STD: Uncertainty estimate (statistical standard deviation) for snow water equivalent retrieval

Layer 1 and 2 coding and legend are described in

Table 4.2 and Table 4.3, respectively. An example of the SWE product is shown in Figure 4.1 with the corresponding uncertainty estimate in Figure 4.2.

Table 4.2: Coding and legend for the SWE product, layer 1.

Code(s)	*Description*
0	Bare ground, no SWE retrieved (SWE = 0 mm)
1-500	SWE [mm]
-1	Masked: land areas for which no SWE retrieval attempted
-10	Masked: water (oceans, or water fraction > 50%)
-20	Masked: mountain
-30	Masked: Glaciers / permanent ice
All other values	Not used

Table 4.3: Coding and legend for the SWE product uncertainty, layer 2.

Code(s)	*Description*
0	Zero SWE retrieved
1-250	SWE_STD (standard deviation) [mm]
-1	Masked: land areas for which no SWE retrieval attempted
-10	Masked: water (oceans, or water fraction > 50%)
-20	Masked: Mountain
-30	Masked: Glaciers/permanent ice
All other values	Not used

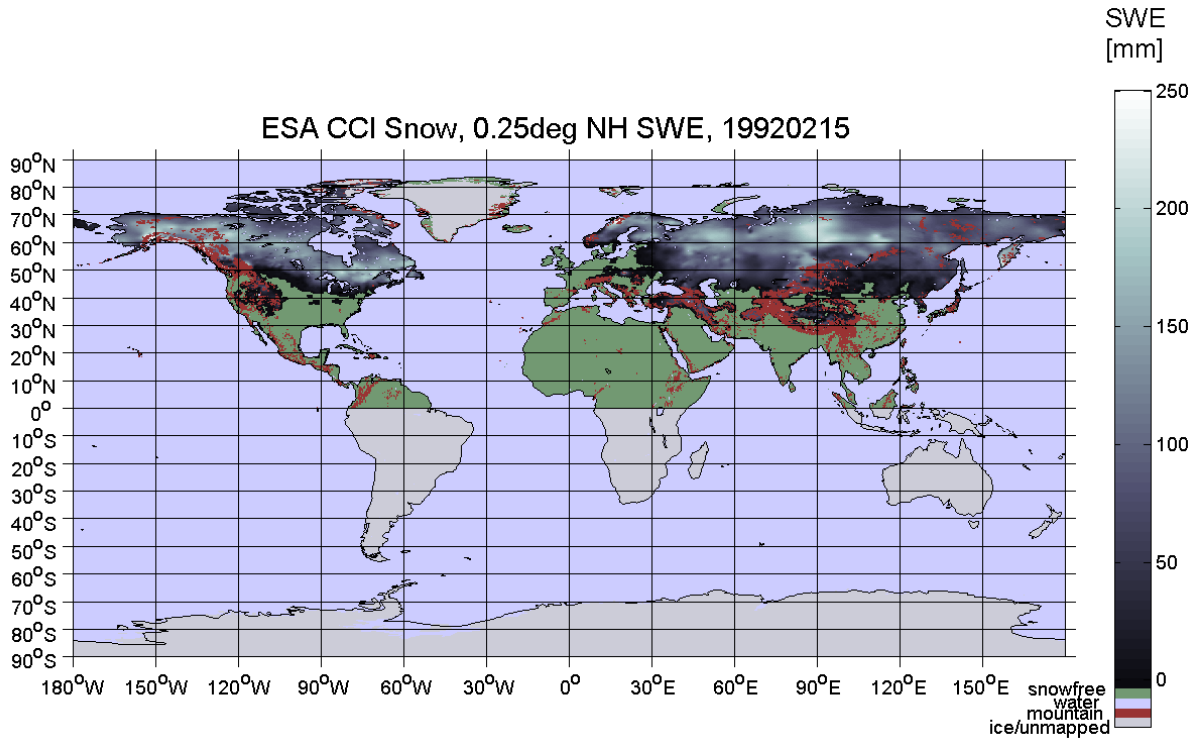

Figure 4.1: Product example, layer 1, snow water equivalent.

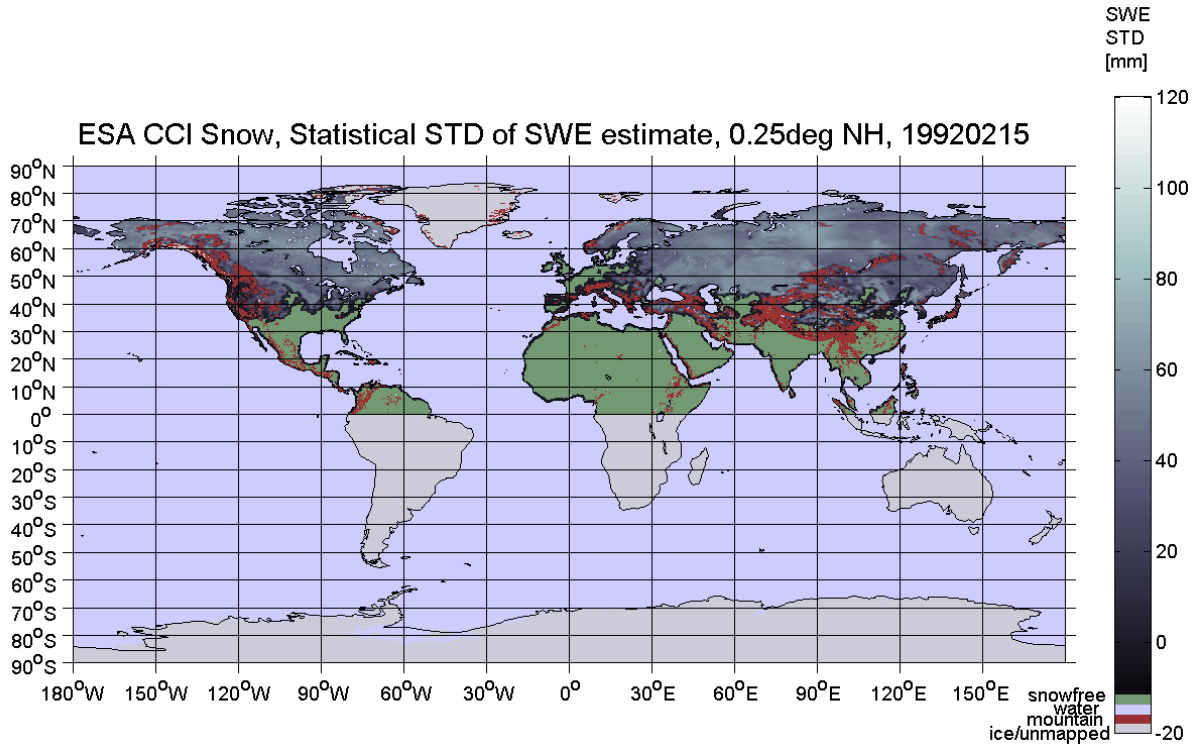

Figure 4.2: Product example, layer 2, estimate of standard deviation of SWE.

4.4. Known Strengths and Limitations

Strengths: As the method utilises passive microwave radiometer data for retrieval of the snow, it is completely unaffected by clouds or light conditions. This combined with the wide swaths of the satellite instruments allow for continuous daily observations of snow without any undue gaps in time series. Using background snow depth, acquired from weather station observations, as an initial guess, allows for much more accurate estimates of snow mass than any method utilising only one source of input data. The dataset is validated against independent snow transect data from Canada, Russia, and Finland. These attributes make the dataset the most accurate long time series on the mass of snow on the Northern Hemisphere.

The uncertainty layer SWE_VAR gives information on how reliable the SWE retrieval has been for the given pixel in the data layer (SWE); it represents the statistical standard deviation of the SWE estimates. If an user has a known threshold for the retrieval accuracy needed to utilise the SWE data in their respective end-user applications, the SWE_VAR field can be used to select the SWE data to be utilised for the users' needs.

Limitations: The algorithm can be used to measure snow packs roughly between 0.05 m and 1.00 m in thickness and only under dry snow conditions. Depth less than 0. 05 m cannot be reliable retrieved because the brightness temperature difference between the two frequencies, falls within 2 K detection precision of the radiometer instruments used. With snow depths greater than 1 m, the brightness temperature signal starts to saturate. Even relatively small amount of liquid water will contaminate the signal making retrieval of SWE impossible. The product is also dependent on the spatial density of the weather station observations available to calculate the background snow depth and snow grain size fields that are applied in SWE retrieval. Where the network is sparse the SWE estimates will also be less accurate, especially in regions where large variations in SWE level are typical (e.g. tundra) and pointwise measurements are unable to catch the typical range of SWE conditions.

Beside limitations caused by signal saturation and availability of weather station data the product is subject to biases caused by using a static snow density value, a necessary simplification. Density of snow usually varies between 100 kg/m^3 (fresh, recently fallen snow) and 400 kg/m^3 (tightly packed mature slab). The used value of 240 kg/m^3 gives good result over continental scale and across the whole snow season but leaves detectable seasonal bias that a user should be aware of. As result SWE values tend to be somewhat overestimated during early accumulation period and underestimated during late winter and melting period. The project team intends to investigate and strives to implement a dynamic snow density consideration for SWE retrieval for the next product version. Additionally, an end user can correct for the static density, if they have actual snow density data, for a region of interest. However, for climate change studies, the static snow density is not a major issue, as a constant snow density consideration will not induce any significant temporal biases in the long-term data record.

5. COMMON FILE FORMAT AND ACCESS DESCRIPTION

5.1. Filename Convention

Filename convention is based on the CCI Data Standards document:

<Indicative Date>-ESACCI-<Processing Level>_<CCI Project>-<Data Type>-
<Product String> [*-<Additional Segregator>*] [*-v<GDS version>*]*-fv<File version>.nc*

Definitions of the filename components are:

- Indicative Date: YYYYMMDD
- Processing Level: L3C for daily SCF and SWE version 1 products
- CCI Project: 'SNOW'
- Data Type: SWE (snow water equivalent); Snow Cover Fraction data types are not yet included in the CCI Data Standards document, but we propose SCFV (viewable snow), SCFG (snow on ground).
- Product String: Identifies the source satellite data for each product. For SCF, this is either AVHRR_MERGED (data spanning 1982-2019) or MODIS-TERRA (data spanning 2000-2019). For SWE, it is SMMR-NIMBUS7 (1979 through May 1987), SSMI-DMSP (October 1987-December 1991), or SSMIS-DMSP (January 1992-May 2019).
- File version: unique identifier increasing with each dataset instance

Note that the 'Additional Segregator' and 'GDS version' are not used as part of the *snow_cci* file names.

5.2. File Format

The metadata are according to the netCDF-4 CF convention. For this version of snow products three CF versions are used (version 1.8 for SCF/MODIS; version 1.9 for SCF/AVHRR and version 1.7 for SWE). In the next version of the products, one and the same version will be used. The conventions define metadata that provide a definitive description of what the data in each variable represents, and the spatial and temporal properties of the data. The data are included in the same file as the data, thus making the file "self-describing". Global and variable attributes are described in the following.

5.2.1. Global Attributes

The global attribute fields for the products are described in Table 5.1, with examples for the content.

Table 5.1: Example of global attribute fields for a SCFV product v1.0 from MODIS data.

Global Attribute	*Content*
title	ESA CCI snow product level L3C daily
institution	ENVEO IT GmbH

Global Attribute	Content
source	TERRA MODIS, Collection 6.1: calibrated radiances 5-min L1B swath data, 1 km (MOD021KM) and geolocation fields 5-min L1A swath data, 1 km (MOD03)
history	2020-10-22: ESA *snow_cci* processing line SCFV, version 1.0
references	http://snow-cci.enveo.at/
tracking_id	ffc2f859-e20b-4a86-a23e-97079c541894
Conventions	CF-1.8
product_version	V1.0
format_version	CCI Data Standards v2.2, 2020
summary	The SCF product provides daily information on snow cover fraction (0 – 100 %) per pixel for global land areas except permanent snow and ice areas with about 1 km pixel size. The product is based on medium resolution optical satellite data. In forested areas, the product provides information on snow on the top of the forest canopy. Clouds are masked.
keywords	snow cover, MODIS, TERRA
id	20020331-ESACCI-L3C_SNOW-SCFV-MODIS_TERRA-fv1.0.nc
naming authority	at.enveo
keywords_vocabulary	NASA Global Change Master Directory (GCMD) Science Keywords
cdm_data_type	Swath
comment	The following auxiliary data set is used for product generation: ESA CCI Land Cover from 2000: water bodies and permanent snow and ice areas are masked based on this dataset. Both classes were separately aggregated to the pixel spacing of the SCF product. Water areas are masked if more than 30 percent of the pixel is classified as water, permanent snow and ice areas are masked if more than 50 percent are identified as such areas in the aggregated map.
date_created	20201020T131529Z
creator_name	ENVEO IT GmbH
creator_url	http://enveo.at
creator_email	snowcci@enveo.at
project	Climate Change Initiative - European Space Agency
geospatial_lat_min	-90
geospatial_lat_max	90
geospatial_lon_min	-180
geospatial_lon_max	180
geospatial_vertical_min	0
geospatial_vertical_max	0
geospatial_lon_resolution	0.01
geospatial_lat_resolution	0.01
geospatial_lat_units	degrees_north
geospatial_lon_units	degrees_east
time_coverage_start	20020331T000000Z
time_coverage_end	20020331T235959Z

Global Attribute	Content
time_coverage_duration	P1D
time_coverage_resolution	P1D
standard_name_vocabulary	CF Standard Name Table v76
license	ESA CCI Data Policy: free and open access
platform	TERRA
sensor	MODIS
spatial_resolution	0.01 degree
key_variables	scfv
doi	https://catalogue.ceda.ac.uk/uuid/ef8eb5ff84994f2ca416dbb2df7f72c7

5.2.1. Variable Attributes

Variable attributes include uncertainty information. The uncertainty estimation has been developed alongside the products and is provided as additional layer for each SCF product.

5.2.2. Metadata

As required by the CCI data standards v2.2, 2020, the metadata per daily product must be compliant with CF1.8 and INSPIRE standards. For the SCF products version 1.0, two different CF versions are used (version 1.8 for SCF/MODIS; version 1.9 for SCF/AVHRR). The CCI data standards v2.1, 2019 with metadata compliant with CF1.7 and INSPIRE standards are used for the SWE products version1.0. In the next version of the products, one and the same metadata version will be used.

5.3. Software Tools

All products generated in the frame of the *snow_cci* project are conformal with the CCI data standards and are thus provided in netCDF-4 format. Data are readable by any software tool able to open and read netCDF file format. A list of open source and commercial software tools for reading, displaying and working with netCDF files is available online, at https://www.unidata.ucar.edu/software/netcdf/software.html.

5.4. Product Access and Policy

All official products generated in the *snow_cci* project are shared via the ESA CCI data portal, providing free and open access.

The datasets should be cited following the instructions provided per product at the Centre for Environmental Data Analysis (CEDA) archive, accessible via the project “ESA Snow Climate Change Initiative (snow_cci)” https://catalogue.ceda.ac.uk/uuid/93cf539bc3004cc8b98006e69078d86b.

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