ESA Climate Change Initiative CCI+

Climate Research Data Package

snow cci

Issue 2 / Revision 1

11 January 2021

Deliverable No.:	D4.2
ESA Contract No.:	4000124098/18/I-NB
Science Lead & Prime:	Thomas Nagler, ENVEO IT GmbH, thomas.nagler@enveo.at
Technical Officer:	Anna-Maria Trofaier, ESA-ECSAT, anna.maria.trofaier@esa.int

To be cited as:

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 (2021) ESA CCI+ Snow ECV: Climate Research Data Package, version 2.1, January 2021.

	Name	*Date*
Checked by	Gabriele Schwaizer / ENVEO, Project Manager	2021 / 01 / 08
Authorized by	Thomas Nagler / ENVEO, Science Leader	2021 / 01 / 08
Accepted by	Anna Maria Trofaier / ECSAT, ESA Technical Officer	2021 / 01 / 11

This document is not signed. It is provided as electronic copy.

ESA STUDY CONTRACT REPORT

ESA CONTRACT NO:	Subject: ESA Climate Change Initiative CCI+ - SNOW		CONTRACTOR:
4000124098/18/I-NB	Climate Research Data Package		ENVEO
ESA CR ( ) NO:	**STAR CODE:**	**NO OF VOLUMES:** 3 **THIS IS VOLUME NO:** 2	**CONTRACTOR'S REF:** Deliverable D4.2

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 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.

This document describes the outcome of the product generation in the second iteration of the *snow_cci* project. The Climate Research Data Package – time series of products – are produced for snow cover fraction (SCF) based on the sensors MODIS and AVHRR (two separate time series) and for snow water equivalent (SWE) based on the sensors SMMR, SSM/I and SSMIS (one combined time series). The SCF product provides in forested areas two thematic information: snow cover fraction viewable (SCFV) on top of the forest canopy and snow cover fraction on ground (SCFG). In open land, the SCF products are identical. For all products, estimated uncertainty at the per-pixel level is available as a separate data layer in the product.

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

AUTHORS: RUNE SOLBERG, GABRIELE SCHWAIZER, THOMAS NAGLER, MARKUS HETZENECKER, STEFAN WUNDERLE, KATHRIN NAEGELI, CHRISTOPH NEUHAUS, ANDREAS WIESMANN, KARI LUOJUS, MATIAS TAKALA, JOUNI PULLIAINEN, JUHA LEMMETYINEN, MIKKO MOISANDER

ESA STUDY MANAGER: ANNA MARIA TROFAIER / ECSAT	ESA BUDGET HEADING:

Document Change Record

Version	Date	Changes	Originator
1.0 draft	23 / 09 / 2019	First version	Solberg et al.
1.0	19 / 11 / 2019	First version approved by ESA	Schwaizer, G.
2.0 draft	29 / 10 / 2020	Second version	Solberg et al.
2.0	08 / 01 / 2021	Second version including revisions according to feedback from ESA	Schwaizer, G.
2.1	11 / 01 / 2021	Second version approved by ESA	Schwaizer, G.

TABLE OF CONTENTS

This page is intentionally left blank.

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. Purpose and Scope

This document describes the outcome of the product generation in the second iteration of the *snow_cci* project. The outcome is the Climate Research Data Package – time series of products – produced for snow cover fraction (SCF) based on the sensors MODIS and AVHRR (two separate time series) and for snow water equivalent (SWE) based on the sensors SMMR, SSM/I and SSMIS (one combined time series). For SCF, there are two types of products available: (i) the snow cover at the surface in open areas and on top of vegetation cover that is present, such as forest canopies (snow cover fraction, viewable snow – SCFV) and (ii) snow cover on the ground for open land (same as SCFV) and corrected for the masking effect by trees in forested areas (snow cover fraction, snow on the ground – SCFG). Furthermore, for all products there is now available an estimate of the uncertainty of the variable per grid cell. This is included as a separate data layer.

1.2. Document Structure

The snow cover fraction data sets based on optical sensors consisting of MODIS-based SCF and AVHRR-based SCF are described in Chapter 2. Chapter 3 describes the snow water equivalent data set based on three consecutive generations of passive microwave radiometers (PMR).

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 (2019) ESA CCI+ Snow ECV: Climate Research Data Package, version 1.0, November 2019.

[RD-5] Schwaizer, G. S. Metsämäki, M. Moisander, K. Luojus, S. Wunderle, K. Naegeli, T. Nagler, J. Lemmetyinen, J. Pulliainen, M. Takala, R. Solberg, L. Keuris, P. Venäläinen (2020) ESA CCI+ Snow ECV: Algorithm Theoretical Basis Document, version 2.0, October 2020.

[RD-6] 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

AVHRR	Advanced Very High Resolution Radiometer
CCI	Climate Change Initiative
CP	Contractual Phase
DARD	Data Access Requirement Document
DMSP	Defence Meteorological Satellite Program
ESA	European Space Agency
GAC	Global Area Coverage
MetOp	European Meteorological Operational Satellite
MODIS	Moderate resolution Imaging Spectroradiometer
NDSI	Normalized Difference Snow Index
NH	Northern Hemisphere
NOAA	National Oceanic and Atmospheric Administration
PMR	Passive Microwave Radiometer
PVP	Product Validation Plan
SCF	Snow Cover Fraction
SCFG	Snow Cover Fraction, snow on the Ground
SCFV	Snow Cover Fraction, Viewable snow
SMMR	Scanning Multichannel Microwave Radiometer

SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager / Sounder
SWE	Snow Water Equivalent
WGS	World Geodetic System

2. SNOW COVER FRACTION

2.1. MODIS

The *snow_cci* snow cover fraction (SCF) product time series from MODIS covers the period 2000 – 2019. Global SCF products are available at daily temporal resolution with cloud cover flagged. The product is based on 1 km data from the MODIS sensor aboard the Terra satellite (launched 1999). The product version 1.0 includes two SCF variables, each with the associated per-pixel uncertainty estimation [RD-6]:

(i) the viewable snow cover fraction (SCFV) at the surface in open areas and on top of vegetation cover that is present, such as forest canopies, and

(ii) (ii) the snow cover fraction on the ground (SCFG) for open areas and in forested areas, derived by applying a canopy correction for snow cover in forests.

The time series characteristics of MODIS based SCF products are summarized in Table 2.1. Gaps in the time series due to missing MODIS acquisitions are listed in Table 2.2. Specific CRDP characteristics, including the data volumes, DOI and access points for each CRDP from MODIS data are provided in Table 2.3.

Table 2.1: Time series characteristics.

Subject	*Description*
Thematic variable	Snow Cover Fraction Viewable (SCFV) and Snow Cover Fraction on Ground (SCFG)
Retrieval algorithm	SCAmod (Metsämäki et al. 2005, 2012, 2015) adapted and improved for snow_cci [RD-5]
Uncertainty algorithm	Error propagation approach adapted from Salminen et al. (2018) [RD-6]
Satellite(s)	Terra (NASA)
Sensor(s)	MODIS
Geographical domain(s)	Global
Temporal resolution	Daily
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
File format	NetCDF4, CF-v1.8
Product version	Version 1.0

Table 2.2: Data gaps in the TERRA MODIS time series.

Start date	End date	Reason
06.08.2000	17.08.2000	No Terra MODIS acquisitions available
16.06.2001	02.07.2001	No Terra MODIS acquisitions available
20.03.2002	27.03.2002	No Terra MODIS acquisitions available
15.04.2002	15.04.2002	No Terra MODIS acquisitions available
17.12.2003	23.12.2003	No Terra MODIS acquisitions available
21.12.2008	22.12.2008	No Terra MODIS acquisitions available
19.02.2016	27.02.2016	No Terra MODIS acquisitions available
In every year, there are a few days with missing MODIS tiles or swaths. SCF products are generated in such cases based on the available satellite data even if the spatial coverage is small.		

Table 2.3: MODIS based SCF CRDP v1.0 characteristics.

Subject	SCFV CRDP v1.0 / MODIS	SCFG CRDP v1.0 / MODIS
Data volume	190 GB	189 GB
DOI	10.5285/ef8eb5ff84994f2ca416dbb2df7f72c7	10.5285/3b3fd2daf3d34c1bb4a09efeaf3b8ea9
Data catalogue access	https://catalogue.ceda.ac.uk/uuid/ef8eb5ff84994f2ca416dbb2df7f72c7	https://catalogue.ceda.ac.uk/uuid/3b3fd2daf3d34c1bb4a09efeaf3b8ea9

On all MODIS data, a pre-classification was applied to identify snow-free areas. The RMSE for pixels defined as snow free by the pre-classification step is assumed to be zero. In the SCF product and associated uncertainty examples shown in Figure 2.1 to Figure 2.4, the colour coding for these areas is set to transparent, i.e. showing the background map.

The applied snow retrieval algorithm is based on the SCAmod algorithm (Metsämäki et al. 2015), but replacing the constant reflectance values for snow-free forested areas and snow free ground, suggested by Metsämäki et al. (2015), with spatially variable reflectance derived from statistical analyses of a time series of MODIS reflectance values [RD-5].

For all pixels used for the SCF retrieval algorithm (Figure 2.1 and Figure 2.3), the RMSE is calculated per pixel and provided as uncertainty layer (cf. Figure 2.2 and Figure 2.4).

Clouds are detected using a decision-tree based algorithm (Metsämäki 2015), adapted, and extended with additional criteria for better performance on a global scale [RD-5]. The cloud mask per product is also overlaid on the associated uncertainty layer.

In all SCF products and the associated uncertainty layers, water bodies and land ice are masked using a static mask derived from the ESA CCI LandCover product for the year 2000 (ESA Land Cover CCI project team; Defourny 2016).

Further, pixels with large solar zenith angles (> 83°) are classified as (polar) night and are masked in all layers. Also, pixels with missing or erroneous input data in at least one of the spectral bands' mandatory for the SCF processing chain are masked in all layers.

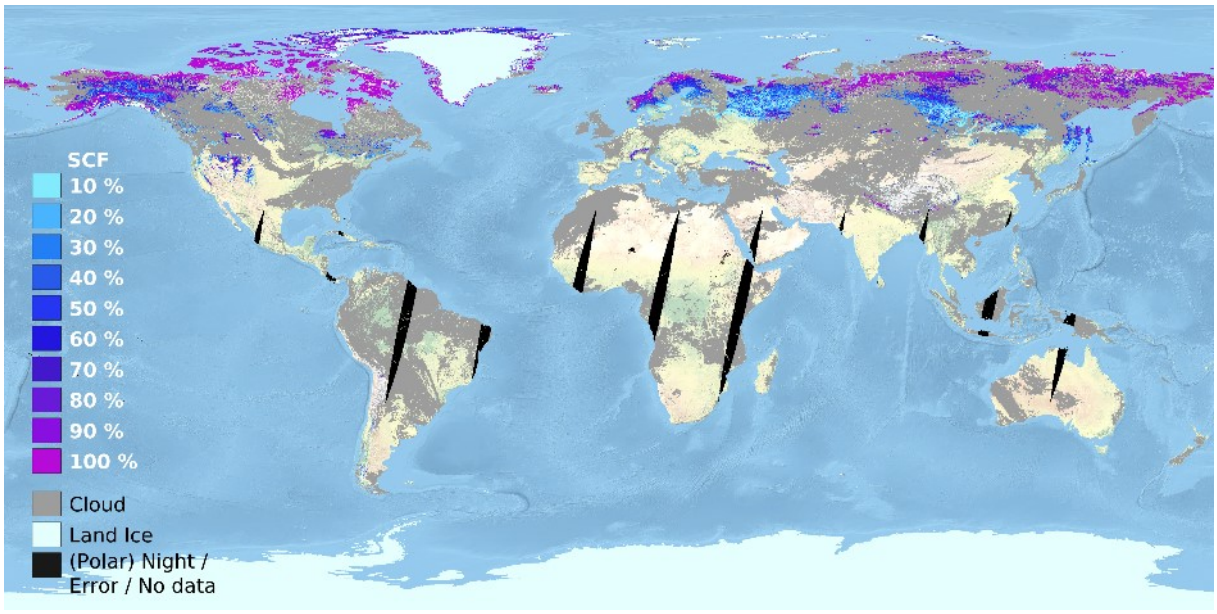

Figure 2.1: Example of SCFV product from Terra MODIS data of 31 March 2002.

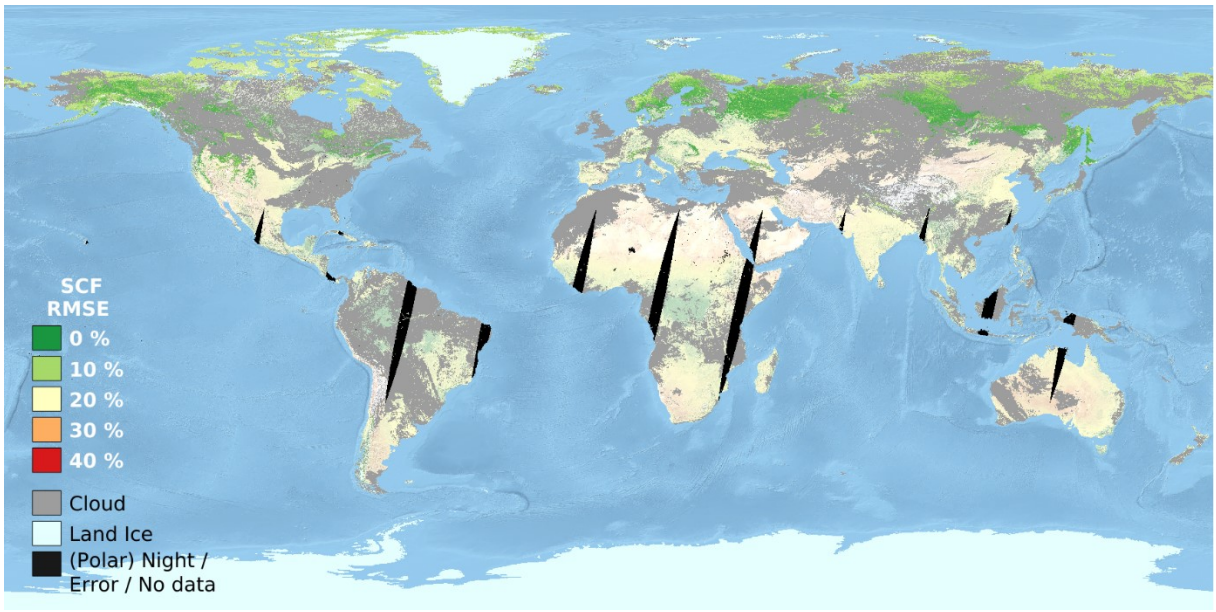

Figure 2.2: Example of corresponding SCFV uncertainty layer from Terra MODIS data of 31 March 2002. The RMSE for pixels defined as snow free by the pre-classification step is assumed to be zero and are set to transparent in the colour coding. For all pixels used for the SCFV retrieval algorithm, the RMSE is provided.

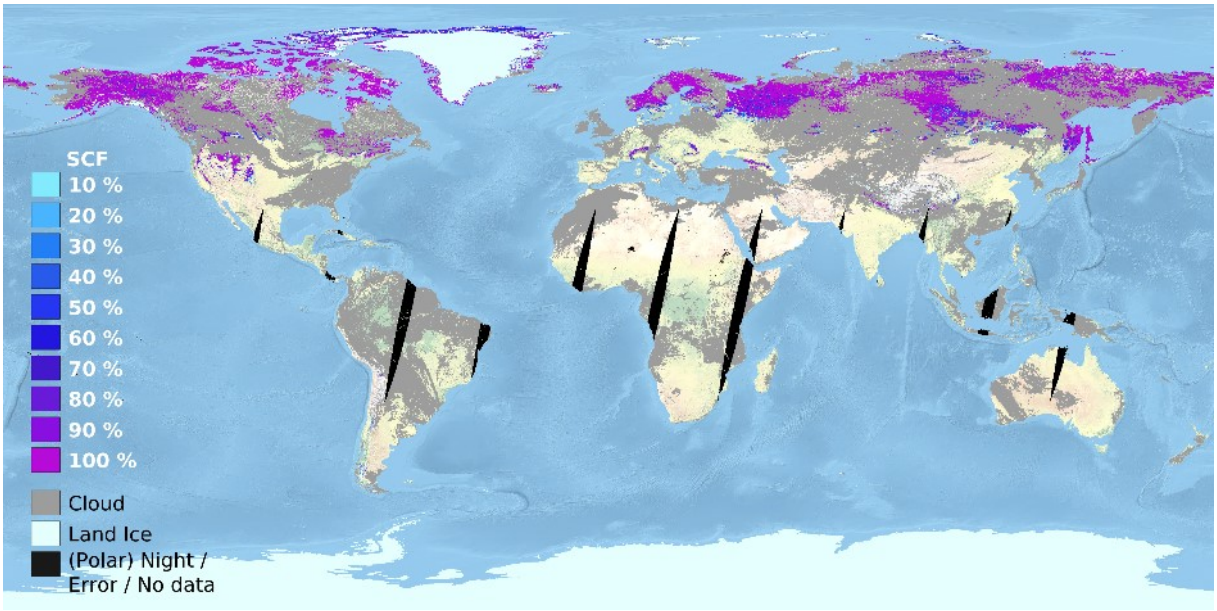

Figure 2.3: Example of SCFG product from Terra MODIS data of 31 March 2002.

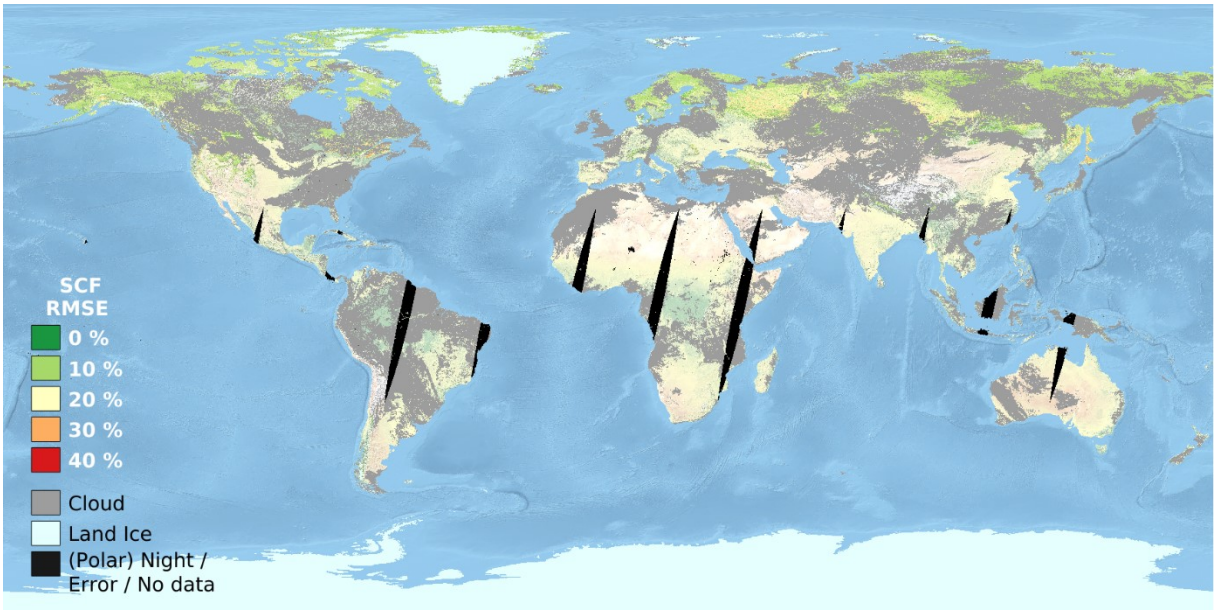

Figure 2.4: Example of corresponding SCFG uncertainty layer from Terra MODIS data of 31 March 2002. The RMSE for pixels defined as snow free by the pre-classification step is assumed to be zero and are set to transparent in the colour coding. For all pixels used for the SCFG retrieval algorithm, the RMSE is provided.

2.2. AVHRR

The aim of the project is the generation of one of the longest snow cover extent time series covering the whole globe. Based on the pre-processed AVHRR GAC (Global Area Coverage) data from the ESA Cloud CCI project, a time series (1982–2019) was generated utilising the fractional snow retrieval algorithm of Salomonson and Appel (2006) as pre-condition (FSC (NDSI) > 5%) before utilizing the SCAmod algorithm (Metsämäki et al. 2015) for viewable snow (SCFV) and snow on ground (SCFG). The procedure is based on the normalised difference snow index (NDSI) and includes a linear scaling of the NDSI values to retrieve fractional snow (viewable snow). A pre-classification was implemented to minimise erroneous results (solar zenith angle > 80°; cloud masks with retrieval uncertainty lower than 20%; water if percentage of pixel > 50 and permanent ice if percentage of pixel > 50). In addition, two thresholds were included to test whether a pixel potentially is snow free or snow covered (snow free if channel 1 > 0.12 or channel 4 > 280 K). Finally, a post-processing for latitudes ±15° and elevations below 1000 m a.s.l. was added (channel 1 < 0.30 or channel 4 > 270 K) to remove erroneous data in the tropical regions. The time series has daily temporal resolution and includes all data sets from the NOAA prime satellites (see Table 2.4) with a spatial resolution of 0.05° (GAC). The SCF time series from AVHRR has no gaps. This version one (V1.0) product includes viewable snow and snow on ground, each with uncertainty estimate. Specific characteristics of the SCF CRPD v1.0 from AVHRR, including data volume, DOI and the access point for the data catalogue, are provided in Table 2.5. Product examples are shown in Figure 2.5 - Figure 2.8.

Table 2.4: Time series characteristics.

Subject	*Description*
Thematic variable	Snow Cover Fraction Viewable (SCFV) and Snow Cover Fraction on Ground SCFG)
Retrieval algorithm	NDSI (Salomonson and Appel 2006) as precondition for SCAmod (Metsämäki et al. 2015)
Uncertainty algorithm	Salberg et al. 2020 [RD-6]
Satellite(s)	NOAA-7, -9, -11, -14, -16, -18, -19
Sensor(s)	AVHRR/2, AVHRR/3
Geographical domain(s)	Global
Temporal resolution	Daily
Start date time series	1 January 1982
End date time series	31 December 2019
Grid size	0.05°
Projection/datum	Geographical (lat/lon)/WGS 84
File format	NetCDF4, CF-v1.8
Product version	Version 1.0

Table 2.5: AVHRR based SCF CRDP v1.0 characteristics.

Subject	SCFV CRDP v1.0 / AVHRR	SCFG CRDP v1.0 / AVHRR
Data volume	34 GB	33 GB
DOI	10.5285/d9df331e346f4a50b18bcf41a64b98c7	10.5285/5484dc1392bc43c1ace73ba38a22ac56
Data catalogue access	https://catalogue.ceda.ac.uk/uuid/d9df331e346f4a50b18bcf41a64b98c7	https://catalogue.ceda.ac.uk/uuid/5484dc1392bc43c1ace73ba38a22ac56

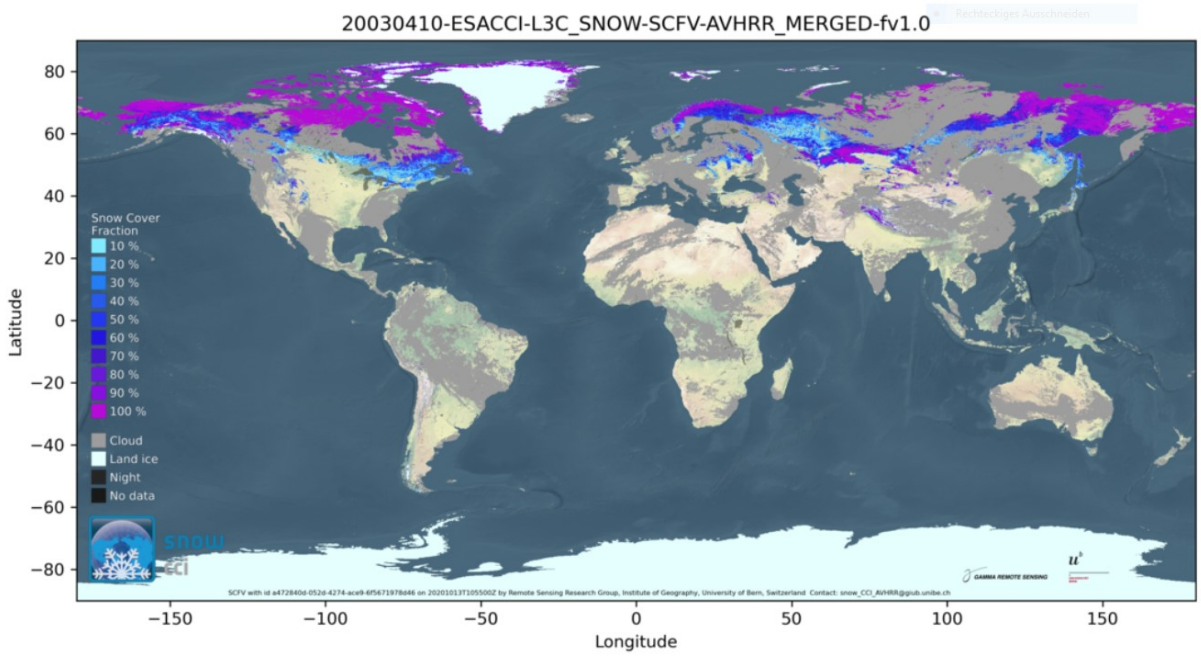

Figure 2.5: Example of SCFV product from AVHRR data of 10 April 2003.

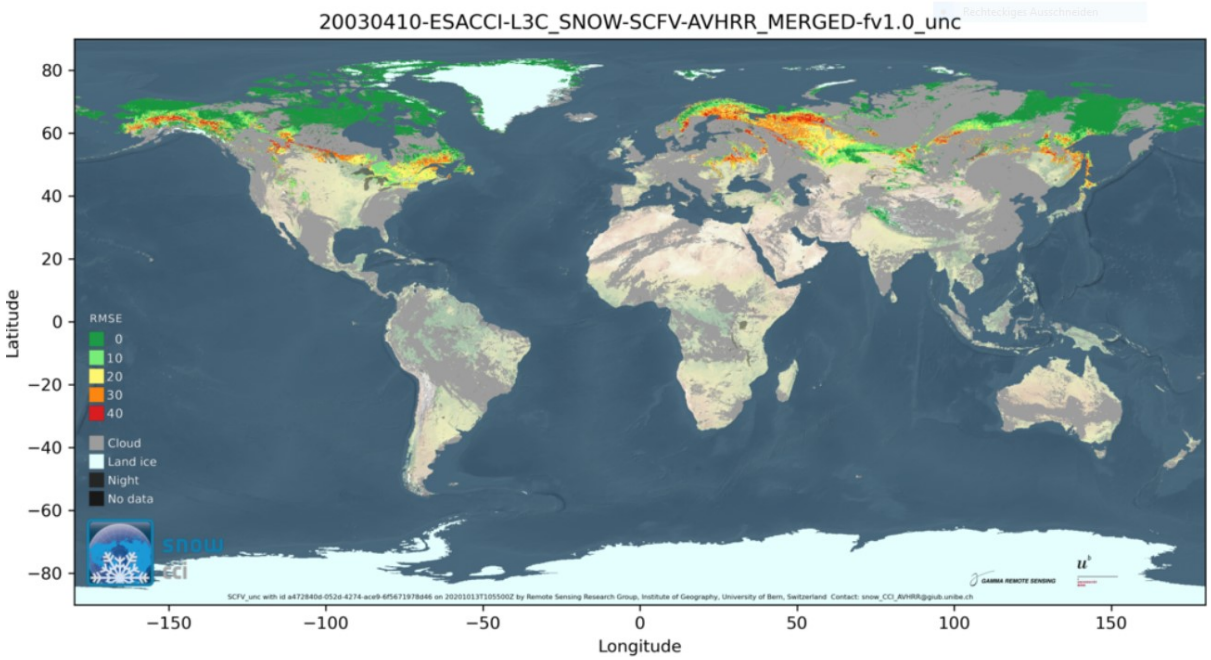

Figure 2.6: Example of corresponding SCFV uncertainty layer from AVHRR data of 10 April 2003.

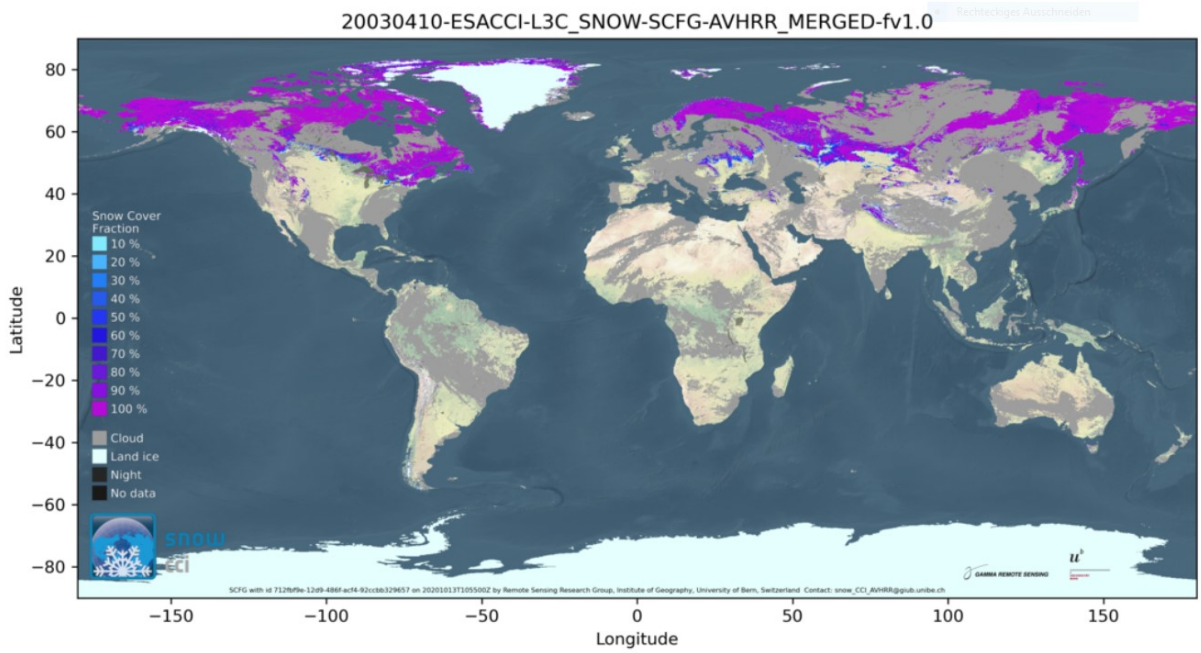

Figure 2.7: Example of SCFG product from AVHRR data of 10 April 2003.

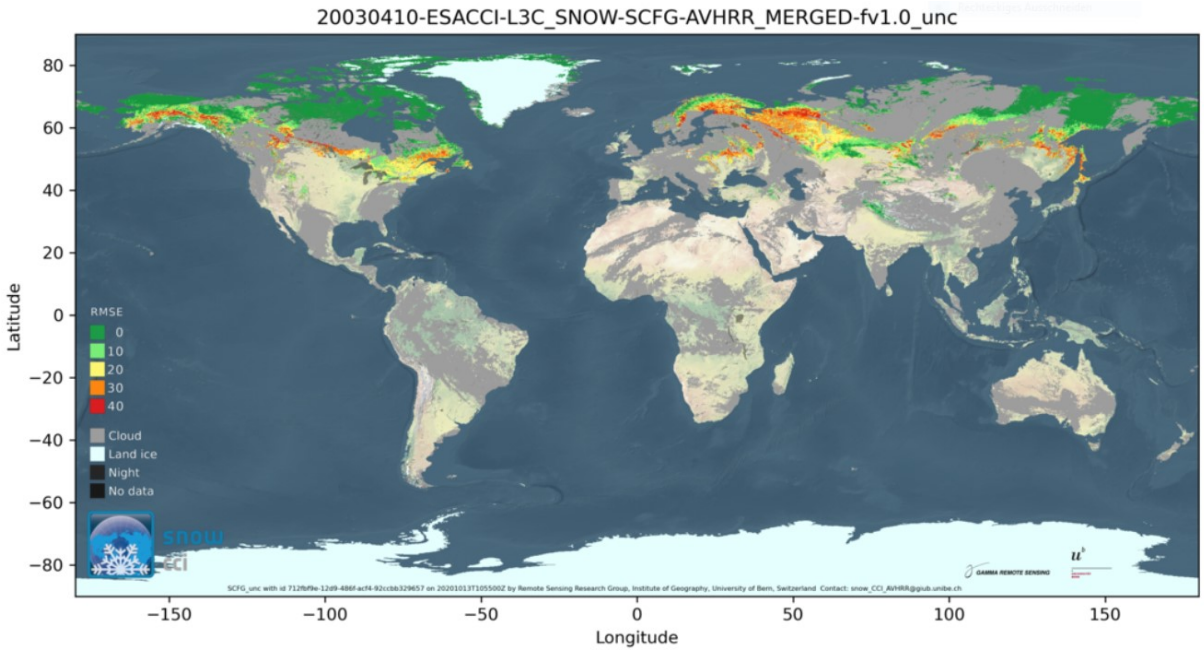

Figure 2.8: Example of corresponding SCFG uncertainty layer from AVHRR data of 10 April 2003.

3. SNOW WATER EQUIVALENT

The *snow_cci* SWE data record, based on methodology by Pulliainen (Pulliainen 2006 and Takala et al. 2011) utilises a data-assimilation-based approach combining space-borne passive microwave radiometer data (SMMR, SSM/I and SSMIS) with data from ground-based synoptic weather stations. The satellite sensors utilised provide data at K- and Ka-bands (19 GHz and 37 GHz respectively) at a spatial resolution of approximately 10 km. The SWE record is produced daily for the period 1988 – 2019, bi-daily for the years 1979 – 1987. SWE information is provided for terrestrial non-mountainous regions of the Northern Hemisphere, excluding glaciers and Greenland (Table 3.1).

Table 3.1: Time series characteristics.

Subject	*Description*
Thematic variable	Snow Water Equivalent (SWE)
Retrieval algorithm	FMI GlobSnow SWE algorithm, (Takala et al. 2011)
Uncertainty algorithm	Takala et al. 2011
Satellite(s)	Nimbus-7, DMSP F8, DMSP F11, DMSP F13 and DMSP F17
Sensor(s)	SMMR, SSM/I and SSMIS
Geographical domain(s)	Northern Hemisphere (excluding mountains/glaciers/ice sheets)
Temporal resolution	Daily (bi-daily for 1979-1987)
Start date time series	6 January 1979
End date time series	31 May 2019
Grid size	0.10°
Projection/datum	Geographical (lat/lon)/WGS 84
File format	NetCDF4, CF-v1.8
Product version	Version 1.1

Table 3.2: Data gaps in the SWE time series.

Start date	*End date*	*Reason*
No SWE retrievals during the NH summer; SWE retrieved during the NH winter season only.		

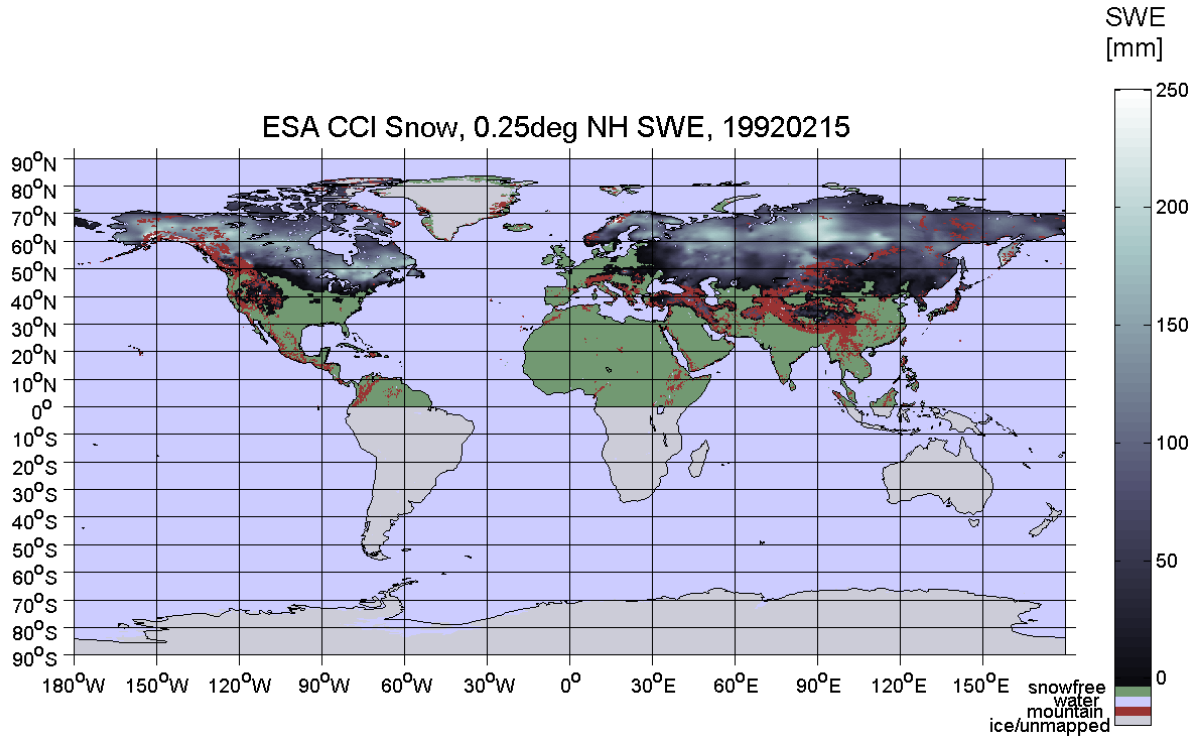

Figure 3.1: Example of SWE product for 15 February 1992.

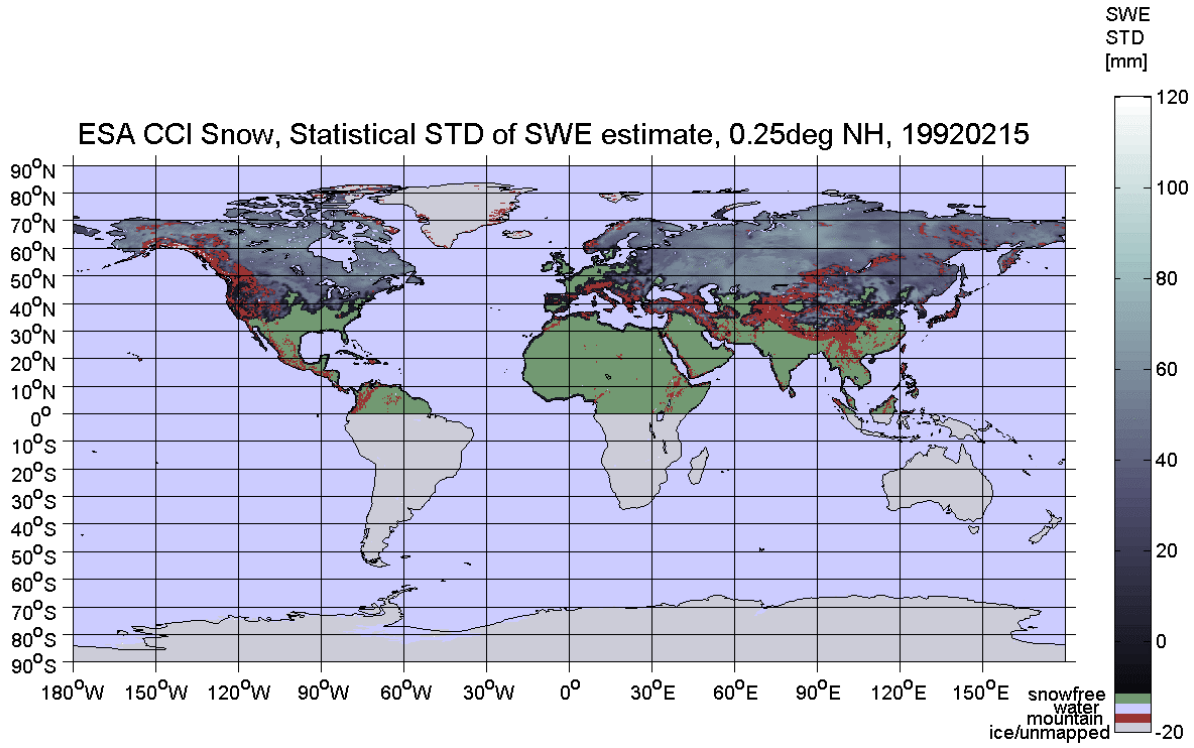

Figure 3.2: Example of corresponding SWE uncertainty layer for 15 February 1992.

4. REFERENCES

ESA Land Cover CCI project team; Defourny, P. 2016. ESA Land Cover Climate Change Initiative (Land Cover CCI) Dataset Collection. Centre for Environmental Data Analysis, date of citation. http://catalogue.ceda.ac.uk/uuid/c19b0914521144ab8c18c91d586c6847

Metsämäki, S., J. Pulliainen, M. Salminen, K. Luojus, A. Wiesmann, R. Solberg, K. Böttcher, M. Hiltunen and E. Ripper. 2015. Introduction to GlobSnow Snow Extent products with considerations for accuracy assessment. *Remote Sensing of Environment*, 156, 96-108.

Pulliainen, J. 2006. Mapping of snow water equivalent and snow depth in boreal and sub-arctic zones by assimilating space-borne microwave radiometer data and ground-based observations. *Remote Sensing of Environment*, 101, 257-269, DOI: 10.1016/j.rse.2006.01.002.

Pulliainen, J., Luojus, K., Derksen, C., Mudryk, L., Lemmetyinen, J., Salminen, M., Ikonen, J., Takala, M., Cohen, J., Smolander, T. and Norberg, J. 2020. Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. *Nature* 581, 294–298. https://doi.org/10.1038/s41586-020-2258-0.

Salminen, M., Pulliainen, J., Metsämäki, S., Ikonen, J., Heinilä, K. (2018). Determination of uncertainty characteristics for the satellite-based estimation of fractional snow cover. *Remote Sensing of Environment*, 212, 103-113.

Salomonson, V., and I. Appel. 2006. Development of the Aqua MODIS NDSI fractional snow cover algorithm and validation results. *IEEE Transactions on Geoscience and Remote Sensing*, 44, 7, 1747 – 1756, 10.1109/TGRS.2006.876029.

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