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User Requirements Document

snow cci

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ESA STUDY CONTRACT REPORT

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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. This document outlines the requirements for *snow_cci* ECVs (snow cover fraction – SCF; snow water equivalent – SWE) obtained through engagement with users from across climate applications, including aspects of hydrology and meteorology. This document provides details on the *snow_cci* user community, snow user requirements which pre-exist the *snow_cci* project, and requirements derived specifically for the *snow_cci* project based on input from the CRG, other CCI projects, the *snow_cci* user requirements workshop, and an online survey to the targeted user community. The consolidated user requirements for *snow_cci* products are provided, and mapped against the baseline specifications of the *snow_cci* products.

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. 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. This document outlines the requirements for *snow_cci* ECVs (snow cover fraction – SCF; snow water equivalent – SWE) obtained through engagement with users from across climate applications, including the detection of variability and trends, climate modelling, and aspects of hydrology and meteorology. The primary parameters to be evaluated are requirements for the GCOS parameters snow extent and snow water equivalent, from which snow depth can be inferred by applying different approaches to estimate snow density.

1.1. Purpose and Scope

This document provides the user requirements for satellite-derived ECVs for fractional snow cover (SCF) across all snow covered regions, and snow water equivalent (SWE) for non-mountain regions. The SWE user requirements specific to mountain snow regions are addressed as part of the *snow_cci* Option 7 User Requirements Document.

The user community for *snow_cci* SCF and SWE products is composed of three primary groups:

- The Climate Research Group (CRG) of the *snow_cci* project team, which conducts case studies on *snow_cci* data usage and act as the interface with the CCI Climate Modelling User Group (CMUG).
- Other CCI projects for which (1) snow is a required input variable in their processing chains such as land surface temperature; permafrost; soil moisture, or (2) snow may feed directly into or support the *snow_cci* processing chain such as *cloud_cci*.
- The broader snow-climate research community, including climate modelling, large-scale hydrology, meteorology, and operational environmental prediction. Note that other segments of the snow science community were not engaged such as local-scale hydrology, transportation and infrastructure, avalanches, etc. in order to retain focus on the global climate aspect of CCI ECVs.

1.2. Document Structure

This document first provides details on the *snow_cci* user community and associated initiatives (Section 2). Snow user requirements from other initiative which pre-date *snow_cci* were surveyed (Section 3.1). Requirements derived specifically for the *snow_cci* project were based on input from the CRG, other CCI projects, and *snow_cci* User Requirements workshops. The first *snow_cci* User Requirements workshops was supported by an online survey to the snow user community, which was

summarized in previous version of the User Requirements Document but is not included in this version. An overall summary is provided in Section 4.

1.3. Applicable and Reference Documents

[AD-1] IGOS Cryosphere Theme Report: http://cryos.ssec.wisc.edu/docs/cryos_theme_report.pdf

[AD-2] The GCOS Essential Climate Variable (ECV) Data Access Matrix: https://www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix

[AD-3] WMO Observing Systems Capability Analysis and Review Tool: https://www.wmo-sat.info/oscar/

[AD-4] Global Cryosphere Watch: https://globalcryospherewatch.org/projects/snowwatch.html

[AD-5] Derksen, C., T. Nagler and G. Schwaizer (2021) ESA CCI+ Snow ECV: User Requirements Document, version 3.0, January 2021 (https://climate.esa.int/documents/1589/Snow_cci_D1.1_URD_v3.0.pdf).

1.4. Acronyms

CCI	Climate Change Initiative
CMIP	Coupled Model Inter-comparison Project
CMUG	Climate Modelling User Group
CNRS	Centre National de la Recherche Scientifique
CRG	Climate Research Group
ECCC	Environment and Climate Change Canada
ECMWF	European Centre for Medium Weather Forecast
ECV	Essential Climate Variable
ERA5	5th major global ECMWF Reanalysis
ESM-SnowMIP	Earth System Model-Snow Model Inter-comparison Project
GCOS	Global Climate Observing System
IGOS	Integrated Global Observing Strategy
OSCAR	Observing Systems Capability Analysis and Review tool
SCA	Snow Covered Area, synonym for SCE
SCE	Snow Cover Extent
SCF	Snow Cover Fraction
SMHI	Swedish Meteorological and Hydrological Institute
SWE	Snow Water Equivalent
TOPC	Terrestrial Observation Panel for Climate
UED	University of Edinburgh
WMO	World Meteorological Organization

2. USERS OF ECV SNOW PRODUCTS

This section provides an overview of the various elements of the *snow_cci* user community (Section 2.1). *Snow_cci* primarily aims to generate products for climate applications across various domains, including climate observations, climate modelling, hydrology, and meteorology. Based on user responses from these communities, requirements for *snow_cci* products were derived (as presented in Section 3). Terrestrial snow user requirements from other international initiatives are also provided as context to *snow_cci* (Section 2.2).

2.1. Users of ECV Snow Products

2.1.1. Climate Research Group

The Climate Research Group (CRG) is an expert advisory group embedded within the *snow_cci* project to provide assessments of the value and significance of products emerging from the project by carrying out climate-relevant use cases. Collectively, the CRG have wide and internationally recognised expertise in observational and modelling studies of seasonal snow dynamics in response to climate variability and change and are ideally placed to assess the value and contribution of the *snow_cci* project for their specific applications. The five case studies are:

1. *Regional and global snow cover trend analysis in support of climate assessments* (lead C. Derksen / ECCC). Analysis of *snow_cci* products are used to estimate both global and regional SCF and SWE trends. Trends from the *snow_cci* products are also compared with observationally constrained land surface models.
2. *Elevation dependence of SWE trends in observations vs regional climate models* (lead M. Ménégoz / IGE; G. Krinner / CNRS). *Snow_cci* products are used to evaluate SWE trends in mountain regions over the historical period for comparison with coupled climate model simulations.
3. *Evaluation of ESM-SnowMIP simulations using snow_cci products* (lead R. Essery / UED). *Snow_cci* products are used to extend the evaluation of snow model simulations over larger regions and longer time periods than detailed in situ measurements are available.
4. *Use of CCI+ snow products to explain impacts of climate change on the hydrological regime in the pan-arctic drainage basin of the Arctic Ocean* (lead D. Gustafsson / SMHI). Snow_cci products are applied to investigate the role of snow cover changes relative to the observed changes in the hydrological regimes (streamflow timing and magnitude) over large pan-arctic drainage basins of the Arctic Ocean.
5. *Multi-decadal comparison between the ECMWF ERA5 climate reanalysis and the snow_cci snow cover data records* (lead P. de Rosnay / EMCWF). *Snow_cci* products are assessed for

their potential contribution to ERA5 ECMWF reanalysis, including potential engagement with other operational centres.

The CRG is also the *snow_cci* interface to the CCI CMUG team, in order to coordinate information exchange on requirements, product specifications, and data sets to support international climate modelling activities. Further details on the CRG case studies are provided annually in the Climate Applications Report (CAR; Deliverable 5.1).

2.1.2. Other CCI Projects

Other CCI projects represent an important user group for *snow_cci* products. Snow is a required input variable in their processing chains. The following CCI projects have provided their requirements for snow products:

- permafrost CCI
- land surface temperature CCI
- soil moisture CCI

2.1.3. Snow-Climate Research Community

There is an extensive user community for satellite-derived ECVs of SCF and SWE spanning diverse disciplines across climatology, hydrology, ecology, and numerical modelling. There is a range of maturity across this community with respect to the use of satellite data, ranging from exploratory research to operational applications. The objective of the user community engagement was to solicit requirements for *snow_cci* from users with a climate focus, and hence the need for consistent, objective, long time series of SCF and/or SWE data covering extensive spatial domains. This includes the evaluation of climate models, land surface modelling (including data assimilation), hydro-climatology, and ecological applications. A *snow_cci* user group email list is maintained for the distribution of product updates. The snow-climate research community is kept informed of snow_cci activities through channels such as the Snow International (SINTER) working group (http://depts.washington.edu/sinter/).

2.2. Related Initiatives

A number of initiatives have compiled requirements for in situ and satellite-derived snow observations. These will be presented in Section 3.1 in order to provide context for the *snow_cci* user requirements. The following initiatives are included:

1. The Global Climate Observing System (GCOS) is a United Nations *Framework* Convention on Climate Change (UNFCCC) sponsored initiative to ensure that adequate global observations are available to support climate related monitoring and research. Three expert panels provide an ongoing focus on the atmosphere, ocean, and land, with terrestrial snow requirements defined and collated by the Terrestrial Observation Panel for Climate (TOPC).

2. The Integrated Global Observing Strategy (IGOS) seeks to strengthen and coordinate satellite and in situ data acquisition in support of global environmental observations. A summary of current and planned capabilities and requirements for terrestrial snow *parameters* was produced as part of an IGOS-Cryosphere theme report (2007).
3. The Observing Systems Capability Analysis and Review Tool (OSCAR) was developed by the World Meteorological Organization (WMO). It links user-defined requirements for earth observation of physical variables (required across weather, water, and *climate* applications) to satellite and surface-based capabilities.

3. USER REQUIREMENTS

This section summarizes snow user requirements from other initiatives as context, before presenting the *snow_cci* user requirements determined from the First User Workshop (held in November 2018) and an accompanying online user survey. The requirements from GCOS, IGOS, and OSCAR (Section 3.1) are necessarily broad, covering a range of applications (of which climate is just one) and techniques (satellite and surface measurements). Conversely, the *snow_cci* requirements (Section 3.2) are more narrowly defined to deliver essential climate variables derived from satellite data. As such, the *snow_cci* requirements occupy part of the broader distribution of snow user requirements.

3.1. Snow Requirements from Other Initiatives

3.1.1. Global Climate Observing System (GCOS)

A summary of GCOS requirements for terrestrial snow ECVs is summarized in Table 3.1. The characteristics for snow covered area (SCA) and SWE are similar: daily data at 1 km resolution, with a more stringent spatial resolution requirement in complex terrain are required. The accuracy requirements are expressed as a percentage for SCA and in absolute terms (mm) for SWE, but the values are similar because 10 mm SWE uncertainty corresponds to 5% to 10% for snow packs with 100 to 200 mm SWE. Unlike the IGOS requirements (Section 3.1.2), there is no consideration within GCOS for how these requirements align with current spaceborne capabilities. For instance, while 1 km is achievable for SCA from existing and heritage optical sensors, there is no appropriate spaceborne measurement at this resolution from which SWE can be derived.

Table 3.1: GCOS Requirements for ECV snow, regarding the parameters snow covered area, snow water equivalent (SWE) and snow depth, according to GCOS Report Nr. 200 (2016).

Product	*Frequency*	*Resolution*	*Measurement Uncertainty*	*Stability*
Snow Covered Area	Daily	1 km 100 m complex terrain	5% (maximum error of omission and commission in snow area) location accuracy better than 1/3 IFOV with target IFOV 100 m in areas of complex terrain, 1 km elsewhere	4% (maximum error of omission and commission in snow area); location accuracy better than 1/3 IFOV with target IFOV 100 m in areas of complex terrain,1 km elsewhere
SWE	Daily	1 km	10 mm	10 mm
Snow Depth	Daily	1 km 100 m in complex terrain	10 mm	10 mm

3.1.2. IGOS

A summary of capabilities and requirements for terrestrial snow parameters (both surface and satellite-derived) from the IGOS-Cryosphere theme report is shown in Table 3.2. Requirements are differentiated between threshold (the minimum necessary) and objective (desired future target) values. As this report was issued in 2007, the progress in satellite snow cover product development is clearly evident relative to the IGOS current/threshold/objective requirements. The 'target' of 0.5 km snow cover information is now 'current' via measurements from MODIS and VIIRS; the objective requirement of 0.1 km is now possible using, for instance, Sentinel-2 measurements. Capabilities for satellite-derived SWE, however, do not approach the threshold requirements as defined by IGOS (e.g. 0.5 km resolution).

Table 3.2: IGOS Summary of current/planned capabilities and requirements for terrestrial snow parameters. C = Current Capability, T = Threshold Requirement (Minimum necessary), O= Objective Requirement (Target), L = Low end of measurement range, U = Unit, H = High end of measurement range, V = Value (http://cryos.ssec.wisc.edu/docs/cryos_theme_report.pdf).

Parameter	C T O	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Snow Cover	C	20	100	%	15-20	%	1	km		day	e.g. MODIS
	T	0	100	%	10	%	0.5	km	1	day	Hydromet
	O	0	100	%	5	%	0.1	km	12	hr	
Snow Water Equivalent, satellite (Shallow)	C	0	0.2	m	2-10	cm	25	km	1	day	e.g. AMSR-E
	T	0	0.3	m	3	cm	0.5	km	6	day	Hydromet
	O	0	0.3	m	2	cm	0.1	km	12	hr	
Snow Water Equivalent, satellite (Deep)	C	none	---	---	---	---	---	---	---	---	Need HF SAR
	T	0.3	3	m	10	%	0.5	km	6	day	Hydromet
	O	0.3	3	m	7	%	0.1	km	12	hr	
Snow Water Equivalent, in situ (Shallow)	C	0	3	m	1	cm	1	m	30	day	Hydromet
	T	0	3	m	1	cm	1	m	7	day	Hydromet
	O	0	3	m	1	cm	1	m	1	day	
Snow Depth, satellite (Shallow)	C	0	~0.7	m	6-35	cm	25	km	1	day	e.g. AMSR-E
	T	0	1	m	10	cm	0.5	km	6	day	Hydromet
	O	0	1	m	6	cm	0.1	km	1	hr	Transportation
Snow Depth, satellite (Deep)	C	none	---	---	---	---	---	---	---	---	Need HF SAR
	T	1	10	m	10	%	0.5	km	6	day	Hydromet
	O	1	10	m	6	%	0.1	km	1	hr	Transportation
Snow Depth, in situ	C	0	10	m	1	cm	1	m	1	day	Hydromet
	T	0	10	m	1	cm	1	m	6	hr	Hydromet
	O	0	10	m	1	cm	1	m	1	hr	

3.1.3. OSCAR

A summary of requirements collated within OSCAR for snow cover and SWE are shown in Table 3.3 and Table 3.4, respectively. Similar to IGOS, the OSCAR requirements differentiate between threshold (minimum requirement), breakthrough (requirements which represents a notable improvement from the threshold), and goal (the ultimate target) requirements. Because OSCAR is a resource which aggregates requirements from various sources and communities, a wide range is evident: for example, the needs of numerical weather prediction are quite different from climate and hydrology. Even within application areas there can be a broad range of requirements. For instance, the requirements defined by CliC and GEWEX, two different climate-oriented projects within the World Climate Research Program, capture different requirements for snow cover and SWE.

Table 3.3: Summary of OSCAR requirements defined for snow cover. (https://www.wmo-sat.info/oscar/variables/view/143). Goal is marked blue, breakthrough green, and threshold orange.

App Area	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness
Climate-AOPC (deprecated)	10 % 13 % 20 %		100 km 200 km 500 km		24 h 2 d 7 d	6 h 12 h 24 h
CLIC (deprecated)	10 % 13 % 20 %		1 km 2.9 km 25 km		24 h 41 h 5 d	7 d 11 d 30 d
GEWEX (deprecated)	10 % 20 % 50 %		15 km 50 km 250 km		24 h 2 d 7 d	30 d 45 d 90 d
Global NWP	10 % 20 % 50 %		5 km 15 km 100 km		3 h 24 h 5 d	3 h 24 h 5 d
High Res NWP	5 % 15 % 20 %		1 km 5 km 20 km		60 min 3 h 12 h	60 min 3 h 12 h
Hydrology	5 % 8 % 20 %		0.1 km 1 km 100 km		24 h 46 h 7 d	24 h 44 h 6 d
Nowcasting / VSRF	10 % 13 % 20 %		5 km 10 km 50 km		60 min 6 h 24 h	60 min 2 h 6 h
Agricultural Meteorology	2 % 4 % 10 %		1 km 2.2 km 10 km		5 d 6 d 7 d	24 h 44 h 6 d
Climate-TOPC (deprecated)	5 % 7 % 10 %		0.1 km 0.45 km 10 km		24 h 3 d 30 d	30 h 3 d 15 d

Table 3.4: Summary of OSCAR requirements defined for snow water equivalent. (https://www.wmo-sat.info/oscar/variables/view/145). Goal is marked blue, breakthrough green, and threshold orange.

App Area	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness
Climate-AOPC (deprecated)	5 mm 6.5 mm 10 mm		100 km 200 km 500 km		24 h 2 d 7 d	6 h 12 h 24 h
CLIC (deprecated)	5 mm 8 mm 20 mm		10 km 13.6 km 25 km		24 h 41 h 5 d	7 d 11 d 30 d
GEWEX (deprecated)	5 mm 10 mm 20 mm		15 km 50 km 250 km		12 h 24 h 7 d	30 d 45 d 90 d
Global NWP	2 mm 10 mm 20 mm		5 km 15 km 100 km		3 h 24 h 5 d	3 h 24 h 5 d
High Res NWP	5 mm 8 mm 20 mm		0.5 km 2 km 20 km		60 min 3 h 6 h	60 min 3 h 24 h
Hydrology	5 mm 8 mm 20 mm		0.1 km 0.464 km 10 km		24 h 46 h 7 d	24 h 44 h 6 d
Agricultural Meteorology	5 mm 23.2 mm 500 mm		30 km 2.2 km 10 km		7 d 11 d 30 d	24 h 46 h 7 d
SIAF (deprecated)	5 mm 10 mm 20 mm		50 km 100 km 500 km		24 h 2 d 7 d	24 h 2 d 7 d
SSLP	5 mm 10 mm 20 mm		50 km 100 km 500 km		24 h 2 d 7 d	24 h 2 d 7 d

3.1.4. Summary of Requirements for Snow Parameters

A synthesis of input from GCOS, IGOS, and OSCAR illustrates the full range of user needs, within which *snow_cci* requirements and product specification occupy a specific niche. For both snow cover extent (SCE) and SWE, there are three general categories of users each with unique requirements: (1) climate, (2) terrestrial applications such as hydrology and agriculture, and (3) numerical weather prediction (NWP). In a general sense, the requirements for climate are relaxed with respect to characteristics such as spatial resolution and latency; NWP needs are most demanding, particularly for regional and/or nowcasting applications. Common requirements across applications are the need for daily data across extensive spatial domains.

The general baseline requirements for ***snow cover*** are daily data at spatial resolutions of at least 1 km with uncertainty of 5 to 10%. Because of the different variables related to snow cover (snow extent; snow covered area; snow cover fraction) it's not always clear from the requirements tables exactly what the uncertainty values correspond to, or how they can be derived.

A distinction in spatial resolution requirements is made between alpine and non-alpine regions due increased snow heterogeneity in complex terrain. The update frequency, latency, and repeat interval vary between applications. Requirements for attributes specific to the derivation of snow cover parameters from optical remote sensing are not provided. For example, there are no user requirements for cloud screening and clearing.

The general baseline requirements for ***snow water equivalent*** are similar to snow extent: daily data with spatial resolution of 1 km with uncertainty of approximately 10%. In some cases, the heritage of SWE retrieval from satellite passive microwave measurements is reflected in a more realistically achievable spatial resolution (5 to 25 km), and a distinction between shallow and deep snow. This is similar to the simple versus complex terrain requirements for SCE and reflects the tendency for passive microwave measurements to saturate under deep snow conditions.

In summary, the GCOS requirements represent a reasonable consensus for satellite snow products: daily data at 1 km spatial resolution with 5-10% uncertainty. For snow cover parameters, these align closely with the capabilities of the spaceborne optical measurements used to derive these products. For SWE, the spatial resolution requirements cannot be achieved using satellite data. Product-specific requirements are lacking from the existing user requirements summarized here. This includes user needs related to metadata, data format (file format, projection, etc.), and access. It is also important to note that requirements are available for other snow variables not discussed here, such as snow depth, albedo, and snow wet/dry state (https://www.wmo-at.info/oscar/variables/view/144).

3.2. Requirements from *snow_cci* User Workshops and snow community engagement

User requirements were continually refined during Phase 1 of *snow_cci* through the following engagement activities:

1. A user requirements workshop was held on 29 November 2018 at the Zentralanstalt für Meteorologie und Geodynamik (ZAMG), in Vienna, Austria. The workshop presentations covered product development, processing plans, and baseline specifications for the *snow_cci* Phase 1 SCF and SWE products. Use cases (with associated requirements) were presented by CRG members, representatives of other CCI projects, and the snow-climate user community. There was group discussion to establish consensus on baseline product specifications for *snow_cci* products, approaches to deriving and delivering the uncertainty characterization, priorities for algorithm improvement, and potential approaches for temporal and spatial aggregation of *snow_cci* products.
2. Twenty responses were submitted to an online user requirements survey, sent to a targeted group of respondents covering the three *snow_cci* user categories outlined in Section 2.1. In addition to multiple choice questions, there was the opportunity to provide free-form input,

which was submitted by nearly all respondents. Full results from the online survey were provided in in the Phase 1 URD [see AD-5]. For some product characteristics, a clear consensus was evident in the survey responses; in some cases, the requirements are application-specific and therefore quite broad.

3. A virtual user workshop was held near the end of *snow_cci* Phase 1 (May 2021). Presentations covered the use of *snow_cci* products by the CRG and CMUG, and the development of connections with other CCI datasets (e.g. permafrost). Discussion covered a review of the user requirements in the context of updating the recommendations from the first User Workshop, revisiting the specifications of *snow_cci* Phase 1 products (SCF and SWE), and identifying priority areas of development for Phase 2 products.

Based on the input gathered through the three steps outlined above, the evolution of user requirements was mapped to the specifications of the *snow_cci* products released during Phase 1 (see Section 3.2.1). The user requirements are assessed in the context of developmental plans for Phase 2 in Section 3.2.2.

3.2.1. Baseline snow_cci Parameters

A summary of the *snow_cci* baseline product specifications identified at the outset of Phase 1 before engagement with the user community is provided in Table 3.5. These specifications consider only the basic product parameters and are driven largely by the capability and availability of satellite measurements and algorithms at the outset of *snow_cci* Phase 1. The snow extent related *snow_cci* product is per-pixel fractional snow extent retrieved from optical imagery and expressed as a percentage, which represents a notable improvement over a simple binary snow/no-snow classification. SWE is derived from a snow depth retrieval from passive microwave measurements converted to SWE via an estimate of snow density.

Table 3.5: *Snow_cci* baseline ECV product specifications used as starting point for discussion with users.

	Snow Extent	*Snow Water Equivalent*
Parameter	Fractional snow extent [%]	Snow mass
Description	Viewable Snow (VS) Snow on Ground (SoG) - forested areas only as VS and SoG are the same in open areas	Snow depth converted to SWE via density
Spatial Coverage	Global (without Antarctica and Greenland ice sheet)	NH non-mountain areas (without Antarctica and all of Greenland)
EO Data	Optical imagery	Passive microwave brightness temperatures
Spatial Resolution	Ca. 4 km Ca. 1 km	Ca. 25 km
Period	1979 – onwards (AVHRR GAC 4 km) 1992-1999 (AVHRR LAC 1 km) 2000 – onwards (MODIS 1 km)	1979 - onwards

	Snow Extent	*Snow Water Equivalent*
Frequency	Daily	Daily
Update Frequency	Annual	Annual
Map Projection	Geographic Grid (Lat/Lon)	Geographic Grid (Lat/Lon)

3.2.2. Requirements for ECV SCF and SWE Products

Requirements for the *snow_cci* products reflect input from the online survey, user workshops, and ongoing engagement with the user community, considered alongside the capabilities of satellite measurements and associated retrieval algorithms. The requirements are summarized in a series of tables, organized by general product characteristics. In each case, requirements met by the *snow_cci* Phase 1 products are highlighted in green rows. Changes to product specifications for CRDPv2 addressed some user requirements not met by CRDPv1. Requirements not met by CRDPv1 or CRDPv2 are flagged through user comments in red rows. These tables will continue to be updated in the subsequent versions of the User Requirement Document. First, temporal and spatial considerations for the SCF and SWE products are summarized in Table 3.6.

Table 3.6: Summary of spatial and temporal requirements for the *snow_cci* products. Green rows indicate decisions made for Phase 1 products; red rows indicate considerations for Phase 2 products.

snow_cci Product Characteristics		*Spatial Domain*	*Spatial Resolution*	*Temporal Coverage*	*Temporal Resolution*	*Update Frequency*	*Other Considerations*
SCF	**CRDPv1**	Global land areas without ice sheets (Antarctica / Greenland)	0.05 deg 0.01 deg	Single-sensor: 1982 onwards 2000 onwards	Daily	Annual	Land / water / surface class map derived from Land Cover CCI provided as additional information (at 0.01 - 0.05 deg)
	CRDPv2	No change	No change	Multi-sensor homogenized dataset	No change	Annual	No change
	Phase 2 considerations to address user requirements	No change	SCE resolution needs are broad, but 0.01 deg meets the majority of needs	User requirement for multi-sensor homogenized dataset	No change	Snow CCI will not address NWP user requirement for near real time processing (6 hours latency)	No change

snow_cci Product Characteristics		Spatial Domain	Spatial Resolution	Temporal Coverage	Temporal Resolution	Update Frequency	Other Considerations
SWE	**CRDPv1**	Northern Hemisphere	0.25 deg Downscaling can be performed by users	1979 onwards	Daily	Annual	Land / water / surface class map derived from Land Cover CCI to be provided as additional information
	CRDPv2	No change	0.125 deg	No change	No change	No change	No change
	Phase 2 considerations to address user requirements	Snow CCI will not meet user needs for southern hemisphere retrievals	Resolution enhancement addresses a clear user requirement		Daily Monthly	Snow CCI will not address NWP user requirement for near real time processing (6 hours latency)	

Phase 1 SWE products covered northern hemisphere non-mountain regions. This addressed all the user needs captured by the online survey and the user workshops, but there is a notable gap for the mountain snow community. To address this gap, work is underway in snow_cci Phase 2 to explore appropriate techniques for adding mountain snow in the SWE product. This will not be achieved by extending the current algorithm, but rather requires a new approach. There are no plans to extend the SWE product to the southern hemisphere because most snow occurs in high elevation or coastal areas which will be alpine and land/sea masked.

Phase SCF products focused on global land areas excluding permanent snow and ice areas and ice sheets (Greenland, Antarctica). Some users have very specific needs that are not currently met, such as the Antarctic dry valleys and islands in the Southern Ocean (e.g. South Georgia). These regions remain under consideration for future product versions. The spatial resolution for SCF is limited by the characteristics of historical optical satellite data. The AVHRR-derived time series from 1979 onward will be at 0.05 degrees resolution, improving to 0.01 degrees starting with the availability of MODIS data in 2000 (there will be products generated from 1km AVHRR LAC data for 1992-1999, but the coverage is not as good as with MODIS starting in 2000). Separate time series at each resolution were processed for Phase 1, but a homogenized multi-sensor dataset will be developed during Phase 2, a priority for many users. SCE resolution requirements span 100 m to 10 km, but the 0.01 to 0.05 resolution range meets the majority of user needs. The SWE CRDPv1 resolution of 0.25 degrees met the majority of climate user requirements. The SWE CRDPv2 product utilized higher resolution and resampled brightness temperatures at 12.5 km resolution, addressing the needs of user who requested

finer grid spacing. Validation experiments quantified improvements in algorithm performance related to the new brightness temperature inputs (Mortimer et al., 2022). The annual CCI product update schedule meets all user requirements, with the exception of operational environmental prediction (e.g. NWP) which requires a latency of <6 hours. This near real time service is not considered to be part of the CCI mandate.

A summary of technical characteristics for the SCF and SWE products is provided in Table 3.7.

Table 3.7: Summary of product requirements for the *snow_cci* products. Green rows indicate decisions made for Phase 1 products; red rows indicate considerations for Phase 2 products.

snow_cci Product Characteristics		*Map Projection*	*File Format*	*Product Access*	*Metadata*
SCF	**CRDPv1**	Geographic Grid (Lat/Lon)	Daily netCDF	CCI portal	
	CRDPv2	No change	No change	No change	
	Phase 2 considerations to address user requirements	No change	No change	Deliver data to Obs4MIPs and ESMValTool	Observation time per pixel added to snow products as layer of the netcdf file
SWE	**CRDPv1**	Geographic Grid (Lat/Lon)	Daily netCDF	CCI portal	
	CRDPv2	No change	No change	No change	
	Phase 2 considerations to address user requirements		No change	Deliver data to Obs4MIPs and ESMValTool	

A geographic (lat / lon) grid, netCDF file format, and ftp data acquisition via the CCI data portal meet the vast majority of user requirements. Only limited metadata requirements were provided by users, but for NWP applications the per-pixel observation time is required. This will potentially be added as a data layer in the Phase 2 products. Other static ancillary data layers such as the land/water mask and land cover class are provided (see Table 3.6). As the products evolve, data flags related to potential cloud-gap filling procedures will be developed. Further efforts to acquire additional metadata requirements from the user community are needed.

A summary of accuracy/uncertainty requirements for the SCF and SWE products is provided in Table 3.8.

Table 3.8: Summary of product uncertainty requirements for the *snow_cci* products. Green rows indicate decisions made for Phase 1 products; red rows indicate considerations for Phase 2 products.

***snow_cci* Product Uncertainty**		***Accuracy Requirement***	***Accuracy Determination***	***Per-pixel Uncertainty***	***Delivery of Uncertainty***
SCF	**CRDPv1**	10-20% Unbiased RMSE	Validation conducted via comparisons with in situ data and high resolution optical imagery	Essential for applications such as data assimilation; derived as part of SCF retrieval	Accuracy determination provided via the Product Validation and Intercomparison Report Uncertainty maps provided as layer in daily netCDF files
	CRDPv2	Reduced RMSE through algorithm enhancements	Development of data flags (clouds, illumination, etc.)	No change	No change
	Phase 2 considerations to address user requirements	Reduced RMSE through algorithm enhancements			
SWE	**CRDPv1**	20-30% unbiased RMSE	Systematic bias estimated via comparison with independent snow course data	Essential for applications such as data assimilation; derived as part of SCF retrieval	Accuracy determination provided via the Product Validation and Intercomparison Report Uncertainty maps provided as layer in daily netCDF files
	CRDPv2	Improved temporal homogeneity achieved through new input passive microwave dataset Dynamic snow density introduced in post-processing	Reported in Mortimer et al. (2022)	No change	No change
	Phase 2 considerations to address user requirements	Evaluation and improvement of of snow accumulation and dynamic snow density treatment			

The extent to which the products meet the accuracy requirements (expressed as unbiased RMSE) is determined through the use of independent reference datasets: snow course data for SWE; in situ snow depth data and high resolution optical imagery for SCF. These validation statistics, along with inter-comparisons with other snow products are reported in the Product Validation and Inter-comparison Report (PVIR; Deliverable 4.1). Additional metrics such as bias are combined with RMSE to provide measures of the systematic error. Per-grid cell uncertainty is produced from the algorithm processing for both SCF and SWE (delivered via the daily netCDF files) and quantifies the random error component. This is described in the End-to-end Uncertainty Budget (E2EUB; Deliverable 2.3). Collectively, the derivation of systematic and random error meets user requirements. Understanding the systematic bias is required for applications such as climate model evaluation, model initialization, and trend determination. Daily, per-grid cell uncertainty is essential for applications such as data assimilation.

A summary of product development requirements for the SCF product is provided in Table 3.9. A primary limitation is the influence of clouds, which obscure the surface and must be masked. There remains no clear user requirement with respect to the filling of cloud-covered areas using measurements from previous days when the surface was viewable (as is done, for instance, with the MODIS Cloud Gap Filled product; Hall et al., 2010). For some users, cloud-gap filling based on a physically based approach is desired, with flags to indicate where and from when cloud-gap filled data were used. These users typically screen for snow (e.g. the CCI soil moisture and LST projects). Other users noted that cloud-gap filling could be done following data acquisition, using in-house tools. Finally, some users noted it is important to not cloud fill for operational applications where a lack of information is preferred over SCF retrievals using some time lag. There was no cloud-gap filling of the SCF product in Phase 1. An option for generating gap-filled SCF products will be proposed later in Phase 2.

Table 3.9: Summary of SCF product development requirements. Green rows indicate decisions made for Phase 1 products; red rows indicate considerations for Phase 2 products.

SCF Product	*Cloud Gap Filling*	*Temporal Aggregation*	*Spatial Aggregation*
CRDPv1	No gap filling	No temporal aggregation (daily data)	None (0.01 and 0.05 deg only)
CRDPv2	No change	No temporal aggregation (daily data)	None (0.01 and 0.05 deg only)
Phase 2 considerations to address user requirements	Physically-based approach with clear QC flagging and uncertainty (planned as option using the CLARA-A3 retrieval) Some applications require no gap filling	Temporal aggregation addresses some user requirements Document tools/methodology for temporal SCF aggregation Flagging required (e.g. number of surface looks within weekly aggregation period)	Aggregation to 0.25 deg for consistency with SWE product Document tools/methodology for spatial SCF aggregation require development Flagging required

There is a user requirement to provide a spatially aggregated 0.1 degree SCF product for consistent analysis of trends and model simulations with the SWE product. The temporal and spatial aggregation of daily SCF products is non-trivial because of the influence of clouds and the computation of 'SCF' from a variable number of clear-sky observations within the averaging window. For Phase 1, the SCF and SWE products were provided on a daily basis with aggregation left to the users. Tool development for aggregation will be considered in Phase 2. Spatially, the methodological approach will need to consider that clouds may obscure all or part of the 0.12 degree grid cells. Temporal aggregation to a weekly product will mitigate the influence of clouds, but a gap-filling scheme remains to be developed. Regardless, clear flagging and metadata will be required to indicate the temporal and spatial provenance of the raw data before aggregation. There was no clear user demand for monthly averaged SCF, given that snow is a dynamic variable, and can evolve from complete snow cover to complete snow-free conditions within a single month.

A summary of product development requirements for the SWE product is provided in Table 3.10.

Table 3.10: Summary of SWE product development requirements. Green rows indicate decisions made for Phase 1 products; red rows indicate considerations for Phase 2 products.

SWE Product	*Alpine Regions*	*Weather Stations*	*Temporal Aggregation*	*Spatial Aggregation*	*Algorithm Enhancements*
CRDPv1	Masked	Weather stations screened for basic consistency criteria. Impact of weather station homogeneity determined via comparison with developmental dataset derived using time series of consistent weather station input	Daily	None (0.25 deg only)	Improved emission models: forest cover; sub-grid lakes
CRDPv2	Masked	Weather stations screened for basic consistency criteria	No change	Determine CMUG needs	Dynamic snow density; enhanced spatial resolution
Phase 2 considerations to address user requirements	Update complex topography mask to be more inclusive of all mountain regions Retrievals for mountain areas under investigation within Option 7	Weather stations screened for basic consistency criteria	Daily Monthly	Development of a fully synergistic SCF+SWE product	Monthly bias-corrected data for February through May based on Pullianen et al., 2020

The SWE product will continue to mask alpine areas; development activities within Option 7 will explore a mountain-specific SWE retrieval approach.

During Phase 1, it was a user requirement to determine the impact of weather station homogeneity on the consistency of the SWE time series. This was addressed by comparing temporally variable weather station input (*snow_cci* v1) with a developmental time series derived using a smaller set of consistent weather station input. This assessment identified very little impact on product performance via the validation statistics (Mortimer et al., 2022). For Phase 2, weather stations used as part of the SWE retrievals must pass quality check standards but will not be fully consistent across the multi-decadal time series. Some users requested a SWE product that does not use any in situ data. This cannot be met because (as shown in SnowPEx) in situ data are mandatory to produce realistic SWE retrievals.

Daily and monthly averaged SWE data will be produced at 0.10 degree resolution. Any further temporal and spatial aggregation will be performed to meet the CMUG requirements.

At present, the SCF and SWE products are fully independent. This means there will be differences in, for example, the snowline location between the two products. These differences will be reflected in climatologies, anomalies, and trends that will not be consistent. For instance, snow extent trends derived from the SCF product will not be the same as snow extent trends derived from the SWE product. A prototype fully synergistic SCF and SWE product will be investigated in Phase 2. There is strong user demand for such a product.

4. SUMMARY OF USER REQUIREMENTS

Consolidated user requirements for *snow_cci* products are provided in Table 4.1 (SCF) and Table 4.2 (SWE), mapped against the baseline specifications of the Phase 1 products.

Table 4.1: Consolidated user requirements for SCF (right column) compared to the *snow_cci* Phase 1 and anticipated Phase 2 product specifications. Green highlighted text indicates agreement between requirement and specification. Yellow highlighted text indicates further development required to meet requirement.

	Snow Cover Fraction Phase 1 Specifications	***Snow Cover Fraction Phase 2 Specifications***	***Snow Cover Fraction User Requirements***
Description	Viewable Snow (snow on top of forest canopy) Snow on Ground (canopy correction applied)	Viewable Snow (snow on top of forest canopy) Snow on Ground (canopy correction applied)	Correction for canopy effects to yield snow on ground information in forested areas.
Spatial Coverage	Global (without Antarctica and Greenland ice sheet)	Global (without Antarctica and Greenland ice sheet)	Global (without ice sheets of Antarctica and Greenland), but include ice free areas in Greenland
Grid Spacing	Ca. 4 km (1982 – present) Ca. 1 km (2000 – present)	Ca. 4 km (1982 – present) Ca. 1 km (2000 – present)	500 m to 1 km
Map Projection	Geographic Grid (Lat/Lon)	Geographic Grid (Lat/Lon)	Geographic Grid (Lat/Lon)
Period	1982 – onwards (4 km) 2000 – onwards (1 km)	1982 – onwards (4 km) 2000 – onwards (1 km)	As long as possible with inter-sensor consistency
Frequency	Daily	Daily (method for temporal aggregation to be developed)	Daily and Weekly
Spatial Aggregation	None	To be determined	0.25 deg CMUG requirement
Update frequency	Annual	Annual	Annual for climate Sub-daily for NRT (Note: NRT services are not the aim of *snow_cci*)
Coding	8-bit (0-255)	8-bit (0-255)	8-bit (0-255)
Format	netCDF	netCDF	netCDF
Accuracy	10-20% RMSE	10-20% RMSE	10-20% RMSE
Uncertainty Metric	Unbiased RMSE	Unbiased RMSE	Unbiased RMSE
Cloud-Gap Filling	None	None (option planned for Phase 2)	Some users request cloud-gap filling
Data Access	CCI data portal (includes ftp)	CCI data portal (includes ftp)	Delivery via ftp
Metadata	Land/sea mask	Land/sea mask Measurement time for MODIS and SLSTR (TBD for AVHRR)	Land/sea mask (common for all products) Measurement time

Table 4.2: Consolidated user requirements for SWE (right column) compared to the *snow_cci* Phase 1 and anticipated Phase 2 products specifications. Green highlighted text indicates agreement between requirement and specification. Yellow highlighted text indicates further development required to meet requirement.

	Snow Water Equivalent Phase 1 Specifications	***Snow Water Equivalent Phase 2 Specifications***	***Snow Water Equivalent User Requirements***
Description	SWE in mm	SWE in mm	SWE in mm
Spatial Coverage	Northern hemisphere non-mountain areas (without Antarctica and all of Greenland)	Northern hemisphere non-mountain areas (without Antarctica and all of Greenland) Development of mountain area product within Option 7	Northern Hemisphere Add mountain areas if possible
Grid Spacing	25 km	12.5 km	Improve grid spacing when possible
Map Projection	Geographic Grid (Lat/Lon)	Geographic Grid (Lat/Lon)	Geographic Grid (Lat/Lon)
Period	1979 – onwards	1979 – onwards	1979 – onwards
Frequency	Daily	Daily Monthly	Daily Monthly
Spatial Aggregation	None	None	Aggregation
Update frequency	Annual	Annual	Annual for climate Sub-daily for NRT (Note: NRT services are not the aim of *snow_cci*)
Coding	8-bit (0-255)	8-bit (0-255)	8-bit (0-255)
Format	netCDF	netCDF	netCDF
Accuracy	20-30% RMSE	20-30% RMSE	10-25%
Uncertainty Metric	Unbiased RMSE	Unbiased RMSE	Unbiased RMSE
Alpine Filling	None	None Under development in Option 7	Separate product with alpine filling and associated flagging
Weather Station Consistency	Evaluated consistency criteria	Basic filtering and consistency criteria	Filtering and consistency to ensure time series homogeneity
Data Access	CCI data portal (includes ftp)	CCI data portal (includes ftp)	Delivery via ftp
Metadata	Land/sea mask	Land/sea mask	Land/sea mask

The majority of climate user requirements are now met by the products, with continued development in later years to address remaining improvements. Note that user requirements for NWP cannot be met within the scope of *snow_cci*.

The year to year evolution of *snow_cci* algorithms, processing, products, and associated user needs feeds into annual updates of the URD. This process captures progress in the *snow_cci* product specifications, and how they align with evolving user requirements. The user community is continually engaged via the CRG, through other CCI projects, and through the *snow_cci* user group.

5. REFERENCES

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Wrzesien, M., M. Durand, T. Pavelsky, S. Kapnick, Y. Zhang, J. Guo, and C. K. Shum. 2018. A new estimate of North American mountain snow accumulation from regional climate model simulations. Geophysical Research Letters. 45: 1423–1432. https://doi.org/10.1002/2017GL076664

A. SECOND (VIRTUAL) USER WORKSHOP AGENDA

Time / CEST	Title	Presenter
13:00 – 13:10	Welcome and introductions	T. Nagler + ESA
13:10 – 13:30	snow_cci project overview and products	T Nagler
13:30 – 13:45	Long Term Trend Analysis of Seasonal Snow	C. Derksen
13:45 – 14:00	Climate change in the High Mountain Asia in CMIP6	M. Lalande
14:00 – 14:15	Use of Snow-CCI products to evaluate simulations at ESM-SnowMIP reference sites	R. Essery
14:15 – 14:30	Role of snow for change in hydrological regimes in Eastern Russian Arctic and subarctic.	D. Gustafsson
14:30 - 14:45	Snow Product Experiments by CMUG	J.-C. Calvet
14:45 – 15:00	Modelling gaps in continental-scale snow estimation as highlighted by land surface model intercomparison	M. Wrzesien
15:00 – 15:15	BREAK	
15:15 – 15:30	The importance of satellite data for climatological snow monitoring in Switzerland	S. Gubler
15:30 – 15:45	Using snow_cci data in the Permafrost_CCI project	S. Westermann
15:45 – 16:00	Use of satellite snow products in gridded snow process models	M. Olefs
16:00 -16:45 min	Review of Requirements of Snow Extent and SWE products for Phase 2 and new snow products Discussion	C. Derksen
16:45 – 17:00	Snow CCI - the way forward & closing of WS	T. Nagler