CCI+ PHASE 1 – NEW ECVS
PERMAFROST

CCN3 OPTION 3
TOWARDS A MULTI-PURPOSE FREEZE/THAW CDR

D1.1 User Requirement Document (URD)

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Executive summary

Within the European Space Agency (ESA), the Climate Change Initiative (CCI) is a global monitoring program which aims to provide long-term satellite-based products to serve the climate modelling and climate user community. Permafrost has been selected as one of the Essential Climate Variables (ECVs) which are elaborated during Phase 1 of CCI+ (2018-2021). As part of the Permafrost_cci baseline project, ground temperature and active layer thickness were considered the primary variables that require climate-standard continuity as defined by GCOS. Permafrost extent and zonation are secondary parameters, but of high interest to users. The ultimate objective of Permafrost_cci is to develop and deliver permafrost maps as ECV products primarily derived from satellite measurements. Algorithms have been identified which can provide these parameters ingesting a set of global satellite data products (Land Surface Temperature LST, Snow Water Equivalent SWE, and landcover) in a permafrost model scheme that computes the ground thermal regime. Annual averages of ground temperature and annual maxima of thaw depth (active layer thickness) were provided at 1km spatial resolution during three phases of Permafrost_cci. The data sets were created from the analysis of lower level data, resulting in gridded, gap-free products. EO data sets are employed to determine the upper boundary condition of the differential equation, while its coefficients (e.g. heat capacity and thermal conductivity) are selected according to landcover information. Derivatives of satellite derived surface status information (Freeze/thaw, FT) are used for consistency analyses.

CCN3 option 3 addresses the need for a FT climate data record of relevance for Permafrost monitoring and as well as further applications. The specific aim of this CCI+ Permafrost subproject is to identify algorithms and datasets which are suitable for the production of a consistent time series. It builds on algorithms developed in the framework of ESA DUE Permafrost and GlobPermafrost, ESA SMOS FT and MethEO. Developments within Snow_cci, Soilmoisture_cci and LST_cci are considered.

This document describes the user requirements and product specification for the FT product characterization. The specific activities of the user requirement analysis include in particular the revision of user questionnaires that were made in the framework of GlobPermafrost and in the first year of the Permafrost_cci baseline project. Further requirements have been collected via literature survey and interaction with relevant ongoing projects with involvement of project team members including ESA Metheo, ESA 4D Greenland, H2020 CHARTER and ERC Q-Arctic.

An FT product should in all cases cover the Arctic as threshold and be global as target. The threshold horizontal resolution ranges from 10 km to 1°, and target in general 100-1km. Subgrid variability is needed for most applications as part of the target product. Freeze/thaw products have been largely defined under the viewpoint of soil moisture product masking and melt state of snow is therefore not considered as a target class. All further applications do however require melting snow in addition. Overall, information of frozen fraction is of added value in addition to the binary frozen/unfrozen information. Products dedicated to snow melt (on land, glaciers and on sea ice) target usually higher level products such as melt extent or melt duration. The unfrozen season length is produced related to permafrost and fluxes/vegetation. The actual melt/thaw state at a certain point in time (before aggregation) should be, however, preserved/provided in addition. Advanced applications even require more information than the binary frozen/melting (melt phases; change of snow properties with refreeze). A commonly agreed benchmark strategy is so far lacking.

1 Introduction

The user requirement document ascertains specific user requirement for the use of EO derived FT products. It provides an overall summary of main findings. User requirements are established by the clear definition of a number of attributes.

1.1 Purpose of the document

This document provides the user requirements for CCN 3 OPTION 3 (option led by b.geos). The URD assesses the requirements of relevant organisations from the Climate Research Community and the Permafrost_cci baseline project. The requirements will be used to guide the product specifications of Permafrost_cci Option 3. In this document, where specific user requirements are identified they are concisely stated and assigned a requirement ID reference code named 'URq_XX'. This allows cross-referencing and traceability between multiple CCI documents.

1.2 Structure of the document

Section 2 of this document details the user community and potential use of a FT CDR service. Results from user surveys and related documents are summarized in Section 3. This also includes the results of the Permafrost_cci baseline survey, which targeted climate modellers and specific use cases. Key issues to fulfil these requirements are discussed in Section 4. A summary of the requirements is presented in Section 5.

1.3 Applicable documents

[AD-1] ESA. 2017. Climate Change Initiative Extension (CCI+) Phase 1 – New Essential Climate Variables - Statement of Work. ESA-CCI-PRGM-EOPS-SW-17-0032.

[AD-2] Requirements for monitoring of permafrost in polar regions - A community white paper in response to the WMO Polar Space Task Group (PSTG), Version 4, 2014-10-09. Austrian Polar Research Institute, Vienna, Austria, 20 pp.

[AD-3] ECV 9 Permafrost: assessment report on available methodological standards and guides, 1 Nov 2009, GTOS-62.

[AD-4] GCOS-200. 2016. The Global Observing System for Climate: Implementation Needs. GCOS Implementation Plan, WMO.

1.4 Reference Documents

[RD-1] Bartsch, A., Matthes, H., Westermann, S., Heim, B., Pellet, C., Onacu, A., Kroisleitner, C., Strozzi, T. 2021. ESA CCI+ Permafrost User Requirements Document, v2.0

[RD-2] National Research Council. 2014. Opportunities to Use Remote Sensing in Understanding Permafrost and Related Ecological Characteristics: Report of a Workshop. Washington, DC: The National Academies Press. https://doi.org/10.17226/18711

[RD-3] GlobPermafrost team. 2016. Requirements Baseline Document. ESA DUE GlobPermafrost project. ZAMG, Vienna

[RD-4] Bartsch, A., Westermann, Strozzi, T., Wiesmann, A., Kroisleitner, C. 2019. ESA CCI+ Permafrost Product Specifications Document, v1.0

[RD-5] van Everdingen, Robert, ed. 1998 revised May 2005. Multi-language glossary of permafrost and related ground-ice terms. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. (http://nsidc.org/fgdc/glossary/; accessed 23.09.2009)

[RD-6] Duchossois G., Strobl, P., Toumazou ,V., Antunes, S., Bartsch, A., Diehl, T., Dinessen, F., Eriksson, P., Garric, G., Houssais, M-N., Jindrova, M., Muñoz-Sabater J., Nagler T., and Nordbeck, O.: User Requirements for a Copernicus Polar Mission – Phase 1 Report, EUR 29144 EN, Publications Office of the European Union, Luxembourg, https://doi.org/10.2760/22832, 2018a.

[RD-7] Duchossois, G., Strobl P., Toumazou V., Antunes, S., Bartsch, A., Diehl, T., Dinessen, F., Eriksson, P., Garric, G., Holmlund, K., Houssais, M.-N., Jindrova, M., Kern, M., Muñoz-Sabater, J., Nagler, T., Nordbeck, O., and de Witte, E.: User Requirements for a Copernicus Polar Mission – Phase 2 Report EUR 29144 EN, Publications Office of the European Union, Luxembourg, https://doi.org/10.2760/44170, 2018b.

[RD-8] Wuite J. et al. (2020) POLAR+ 4DGreenland requirements baseline document. D1.1 v1.0. DTU-ESA-POLAR+4DG-RB-001.

[RD-9] Dodd, E. et al. (2021): Data access requirements document. ESA CCI+ Lakes. V2.0.

[RD-10] Dunbar, R.S. (2018). Soil Moisture Active Passive (SMAP) Mission - Level 3 Freeze-Thaw Passive Product Specification Document. v2. JPL D-56293

[RD-11] Entekabi et al. (2014): SMAP Handbook–Soil Moisture Active Passive: Mapping Soil Moisture and Freeze/Thaw from Space. Publication date: 2014-01.

[RD-12] Rautiainen & Lemmetyinen (2018): SMOS Freeze and Thaw Processing and Dissemination Service - Product Description Document. v1.6

[RD-13] CCI Soil moisture Product Specification Document (PSD) D1.2.1 Version 1.9, 2017

[RD-14] Comprehensive Error Characterisation Report Revision 1 (CECR) D2.2.1 Version 1.0, 2016

1.5 Bibliography

A complete bibliographic list that supports arguments or statements made within the current document is provided in Section 6.1.

1.6 Acronyms

A list of acronyms is provided in section 6.2.

2 Users of landcover underlain by permafrost and related initiatives

The roadmap for a potential FT product is primarily developed for applications considered within the ESA Permafrost_cci project and secondary for further CCI projects. This includes permafrost modelling for production of the climate data records including use cases targeted on improvements of Earth System Models as well as requirements for masking of other CDRs and cross-consistency analyses with other CDRs. The user requirements discussion has been also extended to projects and groups using similar models outside of Permafrost_cci. This includes for example activities in the HORIZON2020 CHARTER and ERC Q-Arctic projects. Mid-winter snow thaw and refreeze is of relevance to various ecological applications and is currently addressed in the HORIZON2020 project CHARTER focusing on Arctic biodiversity. Carbon fluxes are of concern for the ERC Q-Arctic project as well as ESA MethEO.

Previous surveys on Arctic permafrost in the framework of ESA DUE GlobPermafrost [RD-1] have addressed a wide range of potential users in permafrost research what has been reassessed. In addition, requirements by applications related to soil and flux properties are considered. Various EO sources of surface status information need to be considered. Of relevance are MEaSUREs, SMAP, ESA SMOS and EUMETSAT Metop ASCAT services.

3 Users requirements

Surface freeze/thaw as detected by satellites represents either the surface condition of snow/ice or soils. Products represent either the one or the other in general. In case of snow the terms ‘wet/dry’ or ‘frozen/melting’ are used to describe the states. In case of soil ‘frozen/unfrozen’ is detected. Dedicated ‘freeze/thaw’ products mostly address soils and thus acquisitions under snow free conditions, but wet snow information is of added value for such observations due to associated changes in soil temperature beneath the snow pack (e.g. Bartsch et al. 2007, Kroisleitner et al. 2018). Climate change impact can be documented through the length of the unfrozen/snow free season, but spring snow thaw timing and length of snow melt needs to be monitored in addition (e.g. Kouki et al. 2019). [URQ_01]

Documented user requirements regarding snowmelt already exist for polar region applications. Snow and ice sheet melt extent has been listed as high priority parameter in Duchoissois et al. (2018) [RD-6, RD-7] [URQ_02]. Melt extent has been pointed out as required parameter for glaciers, ice sheets and sea ice. Snow melt on sea ice has been recently also discussed in Smith et al. (2021/in review). Location specific melt timing has been stressed as required rather than melt extent for climate model evaluation [URQ_03]. The detection of snow melt start, however, requires specific assumptions to deal with short melt events before the main melt season. This may lead to a bias as quantified in case of seasonal snow (later start determined, Kouki et al. (2019)). Therefore, the non-aggregated observations at measurement time should be preserved [URQ_04]. Mid-winter thaw detection is however also needed for some applications and should be monitored [URQ_05]. For example, rain-on-snow detection is needed for a range of applications (Serreze et al. 2021). Events can affect larger areas, but also a smaller spatial extent can be severe (Bartsch et al. 2010). The median event size over Alaska is less than 500km² (Wilson et al. 2013) what needs to be considered [URQ_06]. Also, the severity of events should be quantified (snow properties change after melt, [URQ_07]). Several classes of melt stages are of interest for glacier monitoring [RD-8] [URQ_08]. This includes phases of the melting process (active melt, refreezing, moistening, ripening and runoff).

A traditional application area of freeze/thaw products is masking of soil moisture. The requirements are in such cases usually aligned with the soil moisture product (spatial and temporal resolution) [URQ_04 and 06]. Further potential of a soil freeze/thaw product includes for example vegetation growing season assessment (Kim et al. 2014, Kim et al. 2020, Hogda et al. 2020), evapotranspiration (Zhang et al. 2011, Kim et al. 2018), fluxes of GHGs (confining the activity period of soil microbes; Bartsch et al. 2007, Kim et al. 2014b) and in combination with GHG concentrations derived from satellites and permafrost (Park et al. 2016, Kroisleitner et al. 2018).

Consolidated requirements for a freeze/thaw product aiming at permafrost research have been so far only stated in [RD-2]. A 100m spatial resolution product in 10 day intervals has been requested [URQ_04 and 06]. Kroisleitner et al. (2018; with focus on Metop ASCAT and SSMI) exemplify that daily resolution is required for ground temperature estimation [URQ_04]. General requirements for a ground temperature product have been collected as part of the Permafrost_cci baseline project [RD-1] which need to be considered in this context. As a threshold, at least the last decade [URQ_09] needs to be addressed as well as the whole Arctic [URQ_10]. Target should be a global product. 10 km and 1 km resolution respectively are needed [URQ_04 and 06].

In order to address the needs of different applications including use by e.g. the climate modelling community a frozen fraction approach is required rather than a frozen/unfrozen classification (Bergstedt et al. 2020, as also defined for permafrost [RD-1]) [URQ_11]. Subgrid information of snowmelt patterns are also of interest in the context of long-term ecosystem monitoring (Rixen et al. 2022). The production of a climate data record may require the combination of products from different satellites. Inconsistencies and systematic differences due to acquisition timing [URQ_04] and differences regarding wavelength and system (active – passive; (Trofaier et al. 2017; static in the beginning, varying towards the end)) need to be investigated [URQ_12].

3.1 Currently available products - soil freeze/thaw

The currently listed freeze/thaw Fundamental Climate Data Record in the WGClimate catalog is the MEaSUREs Global Record of Daily Landscape Freeze/Thaw Status, Version 3 (Kim et al. 2014) and is associated with the ECV soil moisture. It is based on various passive microwave missions (SMMR, SSM/I, and AMSR-E) and thus goes back to 1979. It is characterized by 25km gridding, separation of AM and PM, and >80% mean annual spatial classification accuracy. Binary freeze/thaw information is available. Vegetation related use of the product is suggested apart from soil moisture masking (https://climatemonitoring.info/ecvinventory/). An updated version is available (Kim et al. 2017, 2021)). The same input data are also considered for directly deriving landsurface temperature for the production of climate records within the ESA LST_cci project [RD-9].

Further products exist from SMAP (2015-) and SMOS (2010-) on an operational basis. Both represent L-band missions and are therefore expected to be representative of the upper cm of the soil. Further experimental products exist for Metop ASCAT (C-band radar, 12.5 km gridding), starting 2007. An AMSR-E/AMSR2 based time series is used for a 6 km resolution record currently spanning 2002-2020. Seawinds on QuikScat has been used for products in the context of snow monitoring, specifically spring melt and mid winter melt for 1999-2009 (Bartsch 2010).

- The SMAP mission targets specifically freeze/thaw, complementing soil moisture, and thus requirements have been defined for the mission [RD-10,11]. They have been phrased for the radar instrument (which is now not in operation). Surface binary freeze/thaw state in the region north of 45ºN latitude, which includes the boreal forest zone, was targeted with a classification accuracy of 80% at 3 km spatial resolution and 2-day average intervals. A two- day precision at the spatial scale of landscape variability (~3 km) was originally targeted. The available passive microwave product considers four stages: frozen, thawed, transitional, inverse transitional. The passive microwave product shows >70% accuracy with 36 km gridding (Kraatz et al. 2018).
- The SMOS mission freeze/thaw product provides discrete classes and addresses three stages: thawed, partially frozen or frozen for the northern hemisphere (daily, 25km; [RD-12]).

- A dataset which is aimed at permafrost and flux applications has been developed based on Metop ASCAT (Naeimi et al. 2012). It is available for 12.5 km nominal resolution and considers three states: frozen, unfrozen, melting. The use of C-band radar potentially allows for higher spatial resolution as tested e.g. by Park et al. (2012) for ENVISAT ASAR GM or by Bergstedt et al. (2020) for Sentinel-1. The length of this specific record is however limited and combination with SAR confined to certain regions and time periods.
- A 6 km AMSR-E/AMSR-2 (2002-2020) product covers the northern and southern hemisphere. It has been also created as part of the NASA MEaSUREs program. AM and PM measurements are fused for a daily product. The nominal resolution results from gridding of AMSR-E/AMSR2 native footprints of 14km x 8km and 12km x 7km respectively (Kim et al. 2021). Binary freeze/thaw is available.
- Mid winter thaw and refreeze for areas North of 60° are documented based on Seawinds gridded to 10 km (Bartsch 2010a and b). Daily information on significant snow structure change (yes/no) is aggregated.

The utility of the products varies not only based on different user needs but also based on the retrieval approach and input data. Reanalyses data are commonly used to define a threshold for surface state classification. Naeimi et al. (2012) fit a logistic function to describe the temperature and backscatter relationship. The turning point of the function is considered as threshold. 0°C is applied as threshold for passive records representing the brightness temperature and reanalysis values relationship through a cosine function (Kim et al. 2014, [RD-13,14]). Kroisleitner et al. (2018) found that the passive microwave derived frozen period length differs considerably from Naeimi et al. (2012). Possible reasons are acquisition timing, wavelength and calibration approach. These approaches differ from snowmelt products where for example in case of sea ice a temperature of above -1°C for 3 consecutive days is considered (Smith et al. 2020). Over land, diurnal thaw and refreeze as condition for start of spring melt has been suggested alternatively, but this requires higher repeat measurement intervals than usually available (Bartsch et al. 2007). Most products target 80% detection accuracy [URQ_13]. An actual commonly agreed benchmark for this assessment is so far lacking [URQ_14] what relates partially to lack of representation of variations by the available in situ data within the footprints.

The EUMETSAT ASCAT near real time soil moisture product includes a static daily probability what leads to frequent erroneous masking at high latitudes as the timing of surface state change is highly variable from year to year. The fusion of different soil moisture products can lead also to inconsistent FT flagging over time (Trofaier et al. 2017).

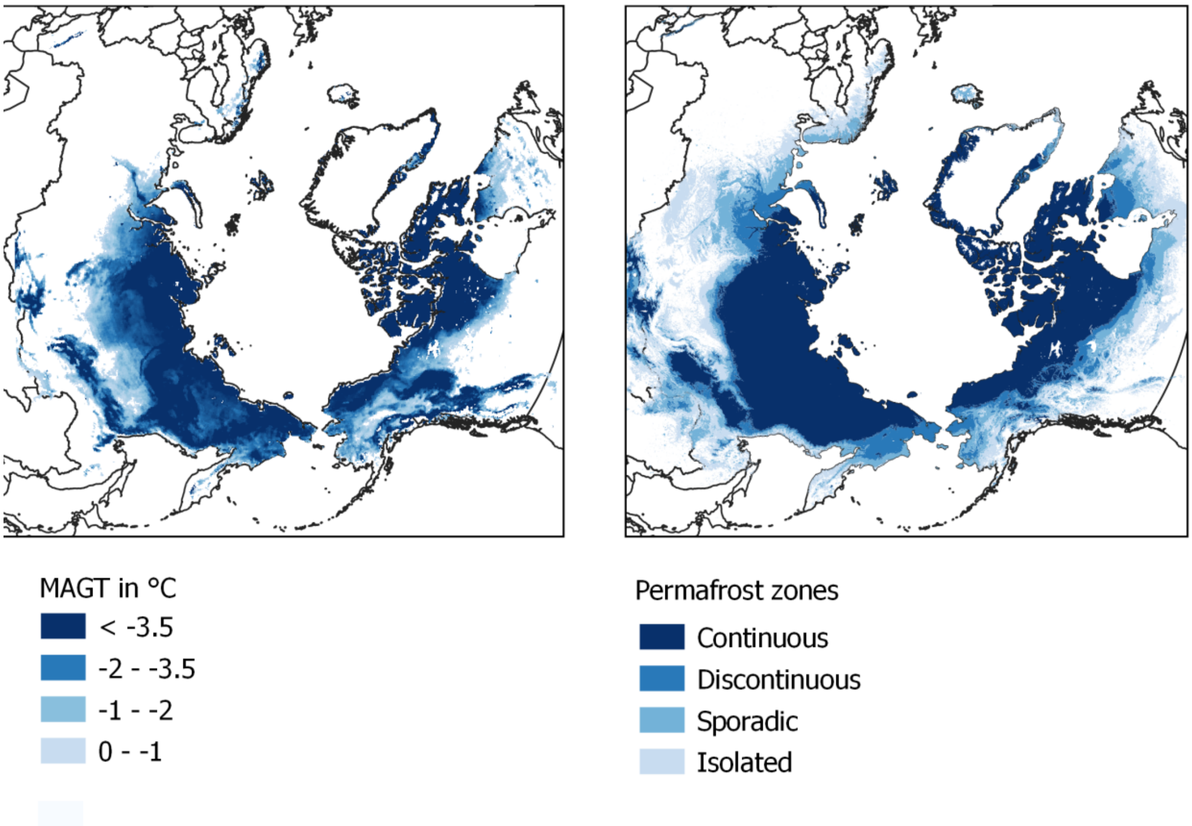

Figure 1: Examples for top of permafrost temperature retrieval and use: left: Surface status based temperature (empirical relationship, ;Metop ASCAT 2007-2011), Kroisleitner et al. 2018; right: Permafrost zones derived from TTOP model with satellite derived land surface temperature (MODIS, 2000-2016; equilibrium approach) as input (Obu et al. 2019). Both generated in the framework of GlobPermafrost.

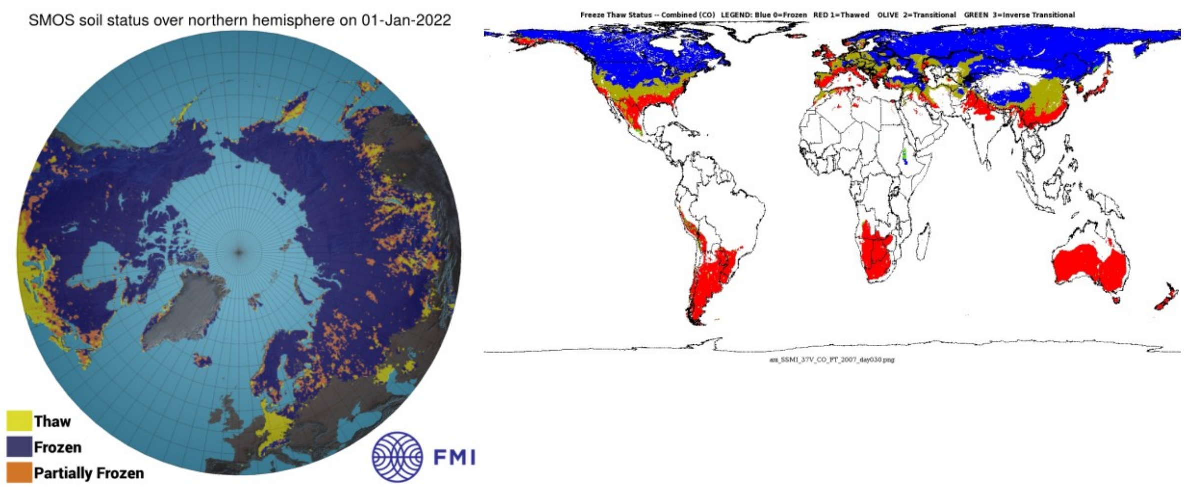

Figure 2: Freeze/thaw product examples which consider several stages: left: SMOS (thawed , frozen, partially frozen); right: SMAP (frozen, thawed, transitional, inverse transitional)[RD-10]

3.2 Summary of user requirements

Table 1. Requirements for a FT CDR for permafrost monitoring in lowland areas (with respect to retrieval approach (Kroisleitner et al. 2018) and in line with Permafrost_cci URD v2.0 ([RD-1] and [RD-2].

	Threshold requirement	Target requirement
	Coverage and sampling	
Geographical coverage	Pan-Arctic	Global with regional specific products
Temporal sampling	annually (aggregated from daily data)	daily
Temporal extent	Last decade	1979 - present
	Thematic content	
Target classes	frozen, unfrozen	frozen, unfrozen, melting
	Resolution	
Horizontal resolution	10 km	100m-1km
Subgrid variability	no	yes
	Error/Uncertainty	
Accuracy	better accuracy than available so far	< 20 % error
Stability	Higher stability than existing datasets	Accuracy needs to be temporally homogeneous
Error characteristics	Independent multi-date validation	Independent multi-date validation

Table 2. Requirements for a FT CRD for masking of soil moisture (RD-2,10,11], Trofaier et al. 2017)

	Threshold requirement	Target requirement
	Coverage and sampling	
Geographical coverage	North of 45°N	Global
Temporal sampling	As soil moisture product	daily
Temporal extent	As length of specific mission	1979 - present
	Thematic content	
Target classes	frozen, unfrozen	frozen, partially frozen, unfrozen (complete)
	Resolution	
Subgrid variability	no	yes
Horizontal resolution	as soil moisture product	as soil moisture product
	Error/Uncertainty	

Accuracy	better accuracy than available so far	< 20 % error
Stability	Higher stability than existing datasets	Accuracy needs to be temporally homogeneous
Error characteristics	Independent multi-date validation	Independent multi-date validation

Table 3. Requirements for a FT CRD for seasonal thaw of snow on land and ice (Duchoissois et al. 2018, ESA Polar+ 4D Greenland Requirements baseline document, [RD-8], Kouki et al. 2019, Smith et al. 2021)

	Threshold requirement	Target requirement
	Coverage and sampling	
Geographical coverage	northern hemisphere	global
Temporal sampling	daily	diurnal
Temporal extent	2000- present	1979 - present
	Thematic content	
Target classes	melt extent (specifically ice sheets & glaciers)	frozen, melting (several melt phases in case of glaciers)
	Resolution	
Horizontal resolution	25km	100m-10km
Subgrid variability	no	yes
	Error/Uncertainty	
Accuracy	better accuracy than available so far	< 20 % error
Stability	Higher stability than existing datasets	Accuracy needs to be temporally homogeneous
Error characteristics	Independent multi-date validation	Independent multi-date validation

Table 4. Requirements for a FT CRD for mid-winter thaw and refreeze (Serreze et al. 2021, Wilson et al. 2013)

	Threshold requirement	Target requirement
	Coverage and sampling	
Geographical coverage	North of 55°N	Global with regional specific products
Temporal sampling	Annually (number of events)	daily
Temporal extent	2000- present	1979 - present
	Thematic content	

Target classes	#events (independent from event/melt duration)	-frozen, melting -impact/severity (snow properties change)
Horizontal resolution	10 km	100-1km
Subgrid variability	no	yes
	Error/Uncertainty	
Accuracy	better accuracy than available so far	< 20 % error
Stability	Higher stability than existing datasets	Accuracy needs to be temporally homogeneous
Error characteristics	Independent multi-date validation	Independent multi-date validation

Table 5. Requirements for a FT CRD for vegetation and carbon flux applications (Böttcher et al. 2018; ESA MethEO project documentation, Bartsch et al. 2007)

	Threshold requirement	Target requirement
	Coverage and sampling	
Geographical coverage	Northern hemisphere	Global
Temporal sampling	annually (aggregated from daily data)	diurnal
Temporal extent	Last decade	1979 - present
	Thematic content	
Target classes	start and end day of year of unfrozen period	frozen, partially frozen, unfrozen (complete), melting snow
	Resolution	
Horizontal resolution	1°	100m-25 km
Subgrid variability	yes	yes
	Error/Uncertainty	
Accuracy	7.5 days for date of freeze-up, less than 1 0% of days with missing data	5 days for date of freeze-up
Stability	Higher stability than existing datasets	Accuracy needs to be temporally homogeneous
Error characteristics	Independent multi-date validation	Independent multi-date validation

3.2.1 Coverage and sampling

An FT product should in all cases cover the Arctic as threshold and be global as target.

3.2.2 Horizontal resolution

The threshold horizontal resolution ranges from 10 km to 1°, and target in general 100-1km. Subgrid variability is needed for most applications as part of the target product.

3.2.3 Thematic content

Freeze/thaw products have been largely defined under the viewpoint of soil moisture product masking and melt state of snow is therefore not considered as a target class. All further applications do however require melting snow in addition. Overall, information of frozen fraction is of added value in addition to the binary frozen/unfrozen information.

Products dedicated to snow melt (on land, glaciers and on sea ice) target usually higher level products such as melt extent or melt duration. The unfrozen season length is produced related to permafrost and fluxes/vegetation. The actual melt/thaw state at a certain point in time (before aggregation) should be, however, preserved/provided in addition. Advanced applications even require more information than the binary frozen/melting (melt phases; change of snow properties with refreeze).

4 User requirements feasibility

The following subsections highlight and revise the user requirements that are judged to be not fully feasible or that need refinement within the scope of the CCN3 option 3.

4.1 General

We identify the following user requirements that are not fully feasible:

URq_06: Horizontal resolution: currently available sensors only allow to meet the threshold requirements, considering a climate data record as the target.

URq_07: Snow properties after refreeze: This requires the availability of specifically short wavelength radar (sensitivity to grain size change) which is of limited availability to date. Research is needed for trade-offs, partially addressing the issue.

URq_08: Several melt/thaw stages representing snow properties on ice: Feasibility is limited to SAR data use. This issue is addressed in ESA 4DGreenland.

4.2 Application specific

We identify the following user requirements that are not fully feasible for specific applications:

Permafrost:

- URQ_06 threshold as well as target horizontal resolution for time period before 2002. But threshold can be met for threshold time range (last decade)

Melt over permanent snow & ice

- URq_08: Several melt/thaw stages representing snow properties on ice as target requirement. But threshold requirement for thematic content can be met.

Mid-winter melt of seasonal snow

- URq_07: Snow properties after refreeze as target requirement. But threshold requirement for thematic content can be met.

5 Summary

All specific user requirements are listed in Table 8. It provides a summary of the identified user requirements that is organised by target type (permanent snow/ice versus seasonal snow/freeze). For each user requirement, the source and the type of work it will address are identified. We aim to meet as many of these requirements as possible in the course of the project time frame, taking into account data availability and workload constraints.

Table 8: *Summary of user requirements.*

ID	PARAMETER	REQUIREMENTS	SOURCES
URQ_01	Seasonal snow/freeze	Thaw and melt information combined, all year	Kroisleitner et al. 2018
URQ_02	All	spatially aggregated product: melt or thaw extent	[RD-6,7]
URQ_03	All	temporally aggregated product: melt or thaw duration	e.g. Kroisleitner et al. 2018, Kouki et al. 2019
URQ_04	All	Temporal resolution: Daily (threshold) to diurnal (target), or as products to be masked	e.g. [RD-10,11] Smith et al. 2021, Kouki et al. 2019,
URQ_05	All	Season: All year	e.g. Serreze et al. 2021
URQ_06	All	Horizontal resolution : threshold 10 km to 1°, and target 100m-1km, or as products to be masked	e.g. [RD1, RD-10,11], Wilson et al. 2013, Böttcher et al. 2018
URQ_07	Seasonal snow/freeze	Snow properties after refreeze	Serezze et al. 2021
URQ_08	Permanent snow/ice	Several melt/thaw stages representing snow properties	[RD-8]
URQ_09	All	Temporal extent: Threshold last decade, target 1979-	[RD-1]
URQ_10	All	Spatial extent: Arctic to global	[RD-1],
URQ_11	Seasonal snow/freeze	Melt/thaw stages with respect to subgrid variability	e.g. [RD-1], Rixen et al. 2022, Bergstedt et al. 2020
URQ_12	All	No inconsistencies over time (also with respect to acquisition timing)	Trofaier et al. 2017
URQ_13	All	>80%	[RD-10,11]
URQ_14	All	Commonly agreed benchmark strategy for accuracy assessment	

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6.2 Acronyms

CCI	Climate Change Initiative
CCN	Contract Change Notice
CRS	Coordinate Reference System
DARD	Data Access Requirement Document
DEM	Digital Elevation Model
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
ESA DUE	ESA Data User Element
FT	Freeze/Thaw
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GST	Ground Surface Temperature
GTOS	Global Terrestrial Observing System
IPA	International Permafrost Association
MAGT	Mean Annual Ground Temperature
MAGT	Mean Annual Ground Surface Temperature
NSIDC	National Snow and Ice Data Center
PSD	Product Specifications Document
RD	Reference Document
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
URD	Users Requirement Document