permafrost
cci

CCI+ PHASE 2 – NEW ECVS
PERMAFROST

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 modeling and climate user community. Permafrost has been selected as one of the Essential Climate Variables (ECVs) which were elaborated during Phase 1 of CCI+ (2018-2021) and continued during Phase 2 of CCI+ (2022-2025).

This novel ECV permafrost product should benefit a wide range of applications and users, thus a thorough user requirement analysis was performed at the beginning of the project which is documented in this report.

The specific activities of the user requirement analysis included a literature review of the documented user requirements to date and the analysis of a user questionnaire that was made available online in October 2018. The questionnaire was designed to capture the needs of so far identified dedicated case studies and specifically climate modelling requirements. The global land modelling community through the Modelling Working Group of the Permafrost Carbon network (PCN) aims to provide synthesized data for assimilation and initialization by biospheric and climate models contributing to IPCC6. Our review further covered user survey results from ESA DUE GlobPermafrost, workshop reports from discussions with representatives of the International Permafrost Association (IPA) and the IPA Action Group 'Specification of a Permafrost Reference Product in Succession of the IPA Map'.

Users demanded a combination of extensive geographical coverage (global permafrost extent 20-30 Mio km^2), high spatial resolution (target resolution 1km) including representation of subgrid variability, high temporal resolution (monthly data) and long temporal coverage (one to several decades back in time). These requirements go considerably beyond the state-of-the-art in remote permafrost ECV assessment, based on published studies and recently demonstrated progress.

Apart from specific accuracy and resolution requirements, the need for the development of a suitable benchmark dataset has been stressed, as it does not exist yet to date.

For Phase 2 recently published requirement updates from GCOS are reviewed in addition. The results of the User Requirements Document (URD) Phase 1 as well as recent updates are summarized in Table 5.

1 INTRODUCTION

1.1 Purpose of the document

This document provides the user requirements of climate science and climate services for ECV products of the Permafrost_cci project. The ultimate objective of Permafrost_cci is to develop and deliver permafrost maps as ECV products primarily derived from satellite measurements.

The URD assesses the requirements of relevant organisations from the Climate Research Community and the International Permafrost Community; the requirements will be used to guide the product specifications of the Permafrost_cci project.

In this document, where specific user requirements are identified they are concisely stated and assigned a requirement ID reference code named 'URq_XX'. This will allow crossreferencing and traceability between multiple CCI documents to be achieved.

1.2 Structure of the document

The first part of this document details the user community and potential use of the permafrost_cci service. User surveys and related documents are summarized in section 3. This also includes the results of the permafrost_cci 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, the Global Observing System for Climate: Implementation Needs (2016
GCOS Implementation Plan, 2015.

[AD-5] GCOS-244, The 2022 GCOS Implementation Plan. 2022.

[AD-6] GCOS-245, The 2022 GCOS ECV requirements. 2022.

1.4 Reference Documents

[RD-1] Bartsch, A.; Grosse, G.; Kääb, A.; Westermann, S.; Strozzi, T.; Wiesmann, A.; Duguay, C.; Seifert, F. M.; Obu, J.; Goler, R.: GlobPermafrost – How space-based earth observation supports understanding of permafrost. Proceedings of the ESA Living Planet Symposium, pp. 6.

[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] IPA Action Group 'Specification of a Permafrost Reference Product in Succession of the IPA Map' (2016): Final report.
https://ipa.arcticportal.org/images/stories/AG_reports/IPA_AG_SucessorMap_Final_2016.pdf

[RD-4] GlobPermafrost team (2017): Summary report from 3rd user Workshop. ESA DUE GlobPermafrost project. ZAMG, Vienna.
https://www.globpermafrost.info/cms/documents/reports/ESA_DUE_GlobPermafrost_workshop_summary_ACOP_v1_public.pdf

[RD-5] GlobPermafrost team (2016): Requirements Baseline Document. ESA DUE GlobPermafrost project. ZAMG, Vienna.

[RD-6] Bartsch, A., Westermann, Strozzi, T., Wiesmann, A., Kroisleitner, C. (2020): ESA CCI+ Permafrost Product Specifications Document, v3.0

[RD-7] 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-8] Bartsch, A., Strozzi, T., Nitze, I. (2023): Permafrost monitoring from space. Surveys in Geophysics.

1.5 Bibliography

A complete bibliographic list that support 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.

1.7 Glossary

The list below provides a selection of terms relevant for the parameters addressed in Permafrost_cci [RD-7]. A comprehensive glossary is available as part of the Product Specifications Document [RD-6].

active-layer thickness

The thickness of the layer of the ground that is subject to annual thawing and freezing in areas underlain by permafrost.

The thickness of the active layer depends on such factors as the ambient air temperature, vegetation, drainage, soil or rock type and total water con-tent, snowcover, and degree and orientation of slope. As a rule, the active layer is thin in the High Arctic (it can be less than 15 cm) and becomes thicker farther south (1 m or more).

The thickness of the active layer can vary from year to year, primarily due to variations in the mean annual air temperature, distribution of soil moisture, and snowcover.

The thickness of the active layer includes the uppermost part of the permafrost wherever either the salinity or clay content of the permafrost allows it to thaw and refreeze annually, even though the material remains cryotic (T < 0°C).

Use of the term "depth to permafrost" as a synonym for the thickness of the active layer is misleading, especially in areas where the active layer is separated from the permafrost by a residual thaw layer, that is, by a thawed or noncryotic (T> 0°C) layer of ground.

REFERENCES: Muller, 1943; Williams, 1965; van Everdingen, 1985

continuous permafrost

Permafrost occurring everywhere beneath the exposed land surface throughout a geographic region with the exception of widely scattered sites, such as newly deposited unconsolidated sediments, where the climate has just begun to impose its influence on the thermal regime of the ground, causing the development of continuous permafrost.

For practical purposes, the existence of small taliks within continuous permafrost has to be recognized. The term, therefore, generally refers to areas where more than 90 percent of the ground surface is underlain by permafrost.

REFERENCE: Brown, 1970.

discontinuous permafrost

Permafrost occurring in some areas beneath the exposed land surface throughout a geographic region where other areas are free of permafrost.

Discontinuous permafrost occurs between the continuous permafrost zone and the southern latitudinal limit of permafrost in lowlands. Depending on the scale of mapping, several subzones can often be distinguished, based on the percentage (or fraction) of the land surface underlain by permafrost, as shown in the following table.

Permafrost	English usage	Russian Usage
Extensive	65-90%	Massive Island
Intermediate	35-65%	Island

Sporadic	10-35%	Sporadic
Isolated Patches	0-10%	-

SYNONYMS: (not recommended) insular permafrost; island permafrost; scattered permafrost.
REFERENCES: Brown, 1970; Kudryavtsev, 1978; Heginbottom, 1984; Heginbottom and Radburn, 1992; Brown et al., 1997.

mean annual ground temperature (MAGT)

Mean annual temperature of the ground at a particular depth.

The mean annual temperature of the ground usually increases with depth below the surface. In some northern areas, however, it is not un-common to find that the mean annual ground temperature decreases in the upper 50 to 100 metres below the ground surface as a result of past changes in surface and climate conditions. Below that depth, it will increase as a result of the geothermal heat flux from the interior of the earth. The mean annual ground temperature at the depth of zero annual amplitude is often used to assess the thermal regime of the ground at various locations. [RD-7]

permafrost

Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years .

Permafrost is synonymous with perennially cryotic ground: it is defined on the basis of temperature. It is not necessarily frozen, because the freezing point of the included water may be depressed several degrees below 0°C; moisture in the form of water or ice may or may not be present. In other words, whereas all perennially frozen ground is permafrost, not all permafrost is perennially frozen. Permafrost should not be regarded as permanent, because natural or man-made changes in the climate or terrain may cause the temperature of the ground to rise above 0°C.

Permafrost includes perennial ground ice, but not glacier ice or icings, or bodies of surface water with temperatures perennially below 0°C; it does include man-made perennially frozen ground around or below chilled pipe-lines, hockey arenas, etc.

Russian usage requires the continuous existence of temperatures below 0°C for at least three years, and also the presence of at least some ice.

SYNONYMS: perennially frozen ground, perennially cryotic ground and (not recommended) biennially frozen ground, climafrost, cryic layer, permanently frozen ground.

REFERENCES: Muller, 1943; van Everdingen, 1976; Kudryavtsev, 1978.

2 USERS OF PERMAFROST DATA AND RELATED INITIATIVES

There are a number of groups who have an interest in data of regional to global permafrost observations. These can generally be divided into:

- Scientists across disciplines which work in permafrost regions, including natural and social sciences, e.g.
    - Climate modellers who are interested in the interactions of permafrost with the climate system and to improve predictions of future changes.
    - Regional permafrost modellers who are using the ECV parameters to validate their models.
    - Remote Sensing Scientists who are investigating landsurface change from satellite observations in permafrost regions
    - Field scientists which require information on the geo-spatial context of the in situ measurements
- Authorities, organisations and projects/initiatives who are interested in the monitoring of permafrost for decision making, e.g. with respect to permafrost-related hazards.

The users of the Permafrost_cci data products cover a relatively broad use of topics and will therefore have a relatively broad range of requirements.

2.1 Climate Research community

The solid and liquid water stored in the ground and at the land surface influences regional climate, its variability and predictability, including effects on the energy and carbon cycles. **CMIP-6**, The Coupled Model Intercomparison Project has become one of the foundational elements of climate science. It consists of a set of common experiments, including historical (1850–2015) and scenario simulations using shared societal development pathways (SSP), in particular upper- and lowend emission scenarios extended until 2300. **CRESCENDO** is Europe's coordinated contribution to CMIP6 with 7 European Earth System Models (ESMs) and 3 European Integrated Assessment Modelling (IAMs) improving and evaluating the representation of key processes in climate and biogeochemistry, including the terrestrial permafrost processes. **LS3MIP** as a particular CMIP6 activity aims to provide a comprehensive assessment of land surface-, snow-, and soil moisture climate feedbacks, and to diagnose systematic biases in the land modules of current ESMs. **ILAMB** is an initiative that feeds into LS3MIP by providing benchmark datasets and software tools for the evaluation of land surface models.

Arctic CORDEX Coordinated Regional Climate Downscaling Experiment produces coordinated sets of regional downscaled climate projections contributing to the WCRP Grand Challenges on Climate Extremes and Regional Climate Information. Within Arctic CORDEX, AWI couples the Regional Arctic Climate Modell HIRHAM with the land community model CLM4 for a better simulation of permafrost extent in the Arctic domain. The development of evaluation techniques is considered a CORDEX priority.

There has been substantial progress in representation of permafrost in climate models in recent years. This includes permafrost mapping with JULES, AWIs coupled regional model HIRHAMCLM, as well as with University of Exeter and Met Office UK (Chadburn et al., 2017a, 2017b). AWI is co-leading the Arctic CORDEX programme and contributing to the WCRP Grand Challenges on Climate Extremes (Matthes et al., 2015) and Regional Climate Information. Matthes et al. (2017) coupled the land model CLM4 and the atmospheric Arctic Regional Climate Model RCM HIRHAM5. Optimization of the evaluation of the simulated permafrost-related variables by climate models is one of the key issues for advancing climate modelling. CMIP5- related studies on permafrost in Global Earth System Models and their land model components like Koven et al. (2012), Slater et al. (2013) or Wang et al. (2016) as well as regional Arctic climate studies looking on impact of permafrost representation like Matthes et al. (2017) evaluated the simulated permafrost extent making use of the IPA permafrost map from 1997 (Brown et al., 1997). A first comparison of a CMIP6 multi-model ensemble with both the ESA DUE GlobPermafrost extent map (Obu et al. 2018, 2019) and (Brown et al., 1997) has been made by Blyth et al. (2020).

The Global Land Modelling Community through the Modelling Working Group of Permafrost Carbon network **PCN** (Schaefer et al., 2014; Koven et al., 2015; McGuire et al., 2016) aims to provide synthesized data for assimilation and initialization by biospheric and climate models contributing to IPCC6.

2.2 International initiatives

Permafrost_cci strives to support the production of consistent and comparable global observations of permafrost what addresses **GCOS** Action T33 [AD-4].

WMO and GCOS delegated the ground-based monitoring of the ECV Permafrost to the Global Terrestrial Network for Permafrost (**GTN-P**) managed by the **International Permafrost Association (IPA)**. GTN-P/IPA established the Thermal State of Monitoring (**TSP**) and the Circumpolar Active Layer Monitoring program (**CALM**), including standards for measurements and data collection. These sites exist throughout the permafrost regions.

The IPA has a Memorandum of Understanding with the Climate and Cryosphere (**CliC**) programme of the World Climate Research Programme (WCRP). The main areas of cooperation are on the roles of permafrost on water and carbon balances, and data assimilation and modelling.

The **Global Cryosphere Watch program of WMO** is an international mechanism for supporting all key cryospheric in-situ and remote sensing observations. CCI+ will support the implementation of guidelines by expressing the need and fostering the process of standardization. This will also support actions within WMO-GCW.

The **Permafrost Carbon Network PCN** funded by the NSF is part of the multi-million dollar Study of Environmental Arctic Change (SEARCH) headed by the University of Alaska Fairbanks. SEARCH is a system-scale, cross-disciplinary research program that seeks to connect the science of Arctic change to decision makers. The Permafrost Carbon Network has been successfully running since 2011 and includes more than 300 scientists from 88 research institutions located in 17 countries. The Permafrost Carbon Network aims at synthesizing existing research about permafrost carbon and climate in a format that can be assimilated by biospheric and climate models, and that will contribute to IPCC6.

3 USER REQUIREMENTS

3.1 Existing requirements surveys and user consultations

User requirements have been gathered within the framework of the ESA DUE Permafrost project, at the DUE-IPA-GTNP-CliC workshop in Frascati in February 2014 and in addition as a community white paper on request by the WMO Polar Space Task Group [AD-2]. A subset of these requirements has been demonstrated within GlobPermafrost and assessed by user organizations. A new user requirements survey has been conducted and published as part of the ESA Living Planet Symposium proceedings (Bartsch et al. 2016c). Required parameters include [RD-1]:

- permafrost extent,
- soil temperature profiles,
- and active layer thickness.

Members of a workshop of the National Research Council in 2014 proposed 100 m resolution in annual intervals as target for circumpolar mapping of permafrost presence [RD-2].

The **open user survey** carried out within the framework of GlobPermafrost in 2016 clearly showed that the

- actual ground temperature (87%) in addition to
- active layer thickness (83%) is of higher interest than
- permafrost fraction (48%).

Spatial resolution of 1 km would be adequate for 35 % of the users, while other would require higher spatial resolution. In GlobPermafrost, global 1km data sets of “Mean Annual Ground Temperature” and “Permafrost probability” (which can be translated to the zonations of continuous, discontinuous and sporadic permafrost) have been compiled. Survey participants showed a high interest for these targeted variables.

More than half of the users consider less than a month time period as a minimum temporal resolution of RS-based permafrost and ground thermal regime product that would be useful for their research. Some users find less than a yearly temporal resolution and fewer a yearly – decadal temporal resolution as a minimum for their research (Figure 1).

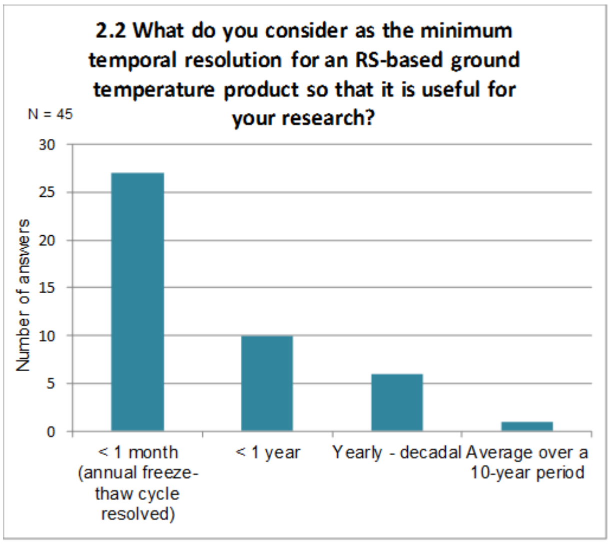

Figure 1: ESA DUE GlobPermafrost user Survey results, question 2.2 [RD-01]

User requirements for permafrost extent have been reviewed with respect to future Copernicus Polar Mission (Table 1 & 2; Duchossois et al. 2018). [URQ_18]

Table 1: Requirements for future missions regarding permafrost extent (Duchossois et al. 2018).

Parameter	AOI	Resolution	Frequency	TL	Unit	Accuracy
Permafrost extent	global	10m [Thr] 1m [Goal]	10yr [Thr] 1yr [Goal]	none time critical	binary	85% [Thr], 95% [Goal]

Further parameters have been listed, but deemed less important regarding capabilities of future missions (Permafrost Table; Taliks; Surface elevation / surface elevation change (Topography); Temperature*; Ice and Liquid Water Content*; Loss (Melt); Surface velocity; Thickness; Mass; Ice Type: pore, segregated, intrusive, vein ice; Heat Conductivity*; Soil composition* (anorganic); Soil composition* (organic)).

3.2 IPA and GTN-P requirements

The IPA permafrost map produced in the 1990ies by Heginbottom et al. (1997) and Brown et al. (1997) is fully established and internationally used in the scientific community and for communication. The IPA permafrost map provided for the first time a visual communication of the areal abundance of permafrost and of its patterns of distribution. The permafrost map has been published as a paper map at a scale of 1:10,000,000. A digital version of the map is available at the

NSIDC. The permafrost map covers the northern hemisphere north of about 30ºN. In general, there is a lack of observations for the southern hemisphere as also stressed in the AR5 of IPCC (IPCC 2013). However, IPA considers the current permafrost map limited and requires new data on mapped permafrost. The current IPA permafrost map has a coarse spatial resolution and is considered imprecise in the definition of permafrost extent [RD-03]. The current IPA permafrost map should not be used to test global models of permafrost and cannot be used to assess change. The current IPA map does not provide data on the Southern hemisphere (Andes, Antarctica, New Zealand).
IPA/GTN-P experts and an extensive expert consultation revealed that a successor product for the IPA permafrost map is required. Requirements are formulated in the IPA report on ‚Specification of a Permafrost Reference Product in Succession of the IPA Map‘ (2016, RD-03):

- a new permafrost map product that is used as data and not for visualization and communication need to have a higher spatial resolution than a map scale of 1:10,000,000. [URq_01]
- The incorporation of time and transient changes of permafrost are important. The mapped permafrost data need to be related to a time stamp. [URq_02]
- The technical form of delivery for maps and data will need to be flexible in adapting to differing communities (e.g., engineering, climate simulation) and evolving needs. [URq_03]
- A high data quality is needed to serve as a reference product for model evaluation, as model input, and as a basis for assessing landscape functioning or hazards. [URq_04]

A joint workshop of GlobPermafrost and the IPA action group on permafrost mapping was held in July 2017 at the Second Asian Conference on Permafrost (ACOP), Hokkaido, Japan.
The following **issues** have been raised [RD-4]:

- There have been concerns regarding round robin exercises since there is currently no suitable benchmark dataset. A benchmark dataset needs to be developed in cooperation with GTN-P. [URq_05]
- A publication on the evaluation of a satellite derived map needs to include contributions from the community. Maps should be reviewed by the respective countries, via GTN-P and the IPA mapping group. [URq_06]
- Terminology needs to be considered. A permafrost map obtained through modelling does only represent potential permafrost distribution. [URq_07]

There has been recently substantial progress in standardization of meta-data records within the framework of activities by GTN-P. IPA-IASC-SCAR Workshops on user requirements for GTN-P standardization were jointly organized by IPA and AWI in the past years. CCI+ needs to support the implementation of guidelines by expressing the need and fostering the process of standardization.

3.2 GCOS requirements

CCI+ Permafrost strives to support the production of consistent and comparable global observations of permafrost what addresses GCOS Action 33 [URq_08]. The required parameters by GCOS for the ECV Permafrost are

- Depth of active layer (m) and
- Permafrost temperature (K).

GCOS Action T34 targets improvements of seasonal soil freeze/thaw (GCOS Action T34, AD-4) Active layer thickness will be included in the permafrost mapping and therefore addresses the need for seasonal soil freeze/thaw.

The ECV Permafrost is currently not listed as 'space-observable' in GCOS-200 [AD-4]. Accuracy requirements are so far formulated only with respect to in situ measurements, also in recent updates [AD-6]:

Table 2: GCOS requirements for (a) ground temperature and (b) active layer thickness ([AD-6], [RD-8])

(a)

	GCOS requirements Threshold	Break-through	Goal
Geographical coverage	-	-	-
Temporal sampling	monthly	daily	hourly
Temporal extent	-	-	-
Horizontal resolution	characterization of bioclimatic zones	transects	regular spacing of boreholes
Subgrid variability	-	-	-
Vertical resolution	50 cm	-	20 cm
Vertical extent	below permafrost table	down to ZAA	deeper than ZAA
Accuracy	0.2 °C	0.1 °C	0.01 °C
Stability	0.1 °C	0.05 °C	0.01 °C

(b)

	GCOS requirements Threshold	Break-through	Goal
Geographical coverage	-	-	-
Temporal sampling	end of thaw period		end of thaw period
Temporal extent	-	-	-
Horizontal resolution	characteri-zation of bio-climatic zone	transects	regular spacing of boreholes
Vertical resolution	20	10	2
Precision	-	-	-
Accuracy	2 / 15 cm *		1 / 5 cm *
Stability	10 cm	5cm	1 cm

* mechanical probing penetration uncertainty/ sensor uncertainty

GCOS requirements have been recently publicly reviewed. Several additions and changes have been submitted. Three new ECV 'gridded' products had been proposed as the above is tailored to in situ observations. Those are: ground temperature, thaw depth and permafrost extent. In addition, the IPA working group recommendations for "Rock glaciers inventories and kinematics" has proposed to GCOS as a new product for the ECV permafrost. Only requests for rock glaciers have been recognized. However, Permafrost extent is mentioned several times in the GCOS strategy document [AD-5] as needed, but no requirements are provided in [AD-6].

3.3 WMO OSCAR database

Threshold and goal requirements for **permafrost extent** and seasonally frozen ground for the climate landsurface community are addressed in the WMO OSCAR database. The measuring unit is defined as %. Performance requirements are listed with respect to the following levels (https://www.wmo-sat.info/oscar/observingrequirements):

- An "optimum" (Opt.) "Goal", or a "maximum" performance level;
- A "threshold" (Thr.) or "minimum", performance level;
- A "breakthrough" (Br.) performance level.

The "maximum" requirement is the value which, if exceeded, does not yield significant improvements in performance for the application in question. Therefore, the cost of improving the observations beyond this requirement would not be matched by a significantly increased benefit. Maximum requirements are likely to evolve; as applications progress, they develop a capacity to make use of better observations.

The "minimum" or "threshold" requirement is the value below which the observation does not yield any significant benefit for the application in question or may even deteriorate the application. As a system that meets only minimum requirements is unlikely to be cost-effective, it should not be used as a minimum target level for an acceptable system. The "breakthrough" level represents the value that would need to be attained to provide a significant benefit for the application, compared with current performance.

Note: In reading the values, goal is marked blue, breakthrough green and threshold orange

Id	Variable	Layer	App Area	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
401	Permafrost	Land surface	Hydrology	5 8.5 25		0.1 km 1 km 100 km		6 h 14 h 3 d	6 h 17 h 6 d	Global land	reasonable	2003-10-20	ET ODRRGOS
675	Permafrost	Land surface	Climate-TOPC (deprecated)	5 7 10		0.25 km 0.85 km 10 km		24 h 36 h 5 d	24 h 36 h 5 d	Global land	firm	2007-07-19	TOPC

Figure 2: WMO OSCAR data base entries for permafrost [URq_09] (source https://www.wmo-sat.info/oscar/variables/view/124)

The "uncertainty" characterizes the estimated range of observation errors on the given variable, with a 68% confidence interval (1σ). No requirements on stability have been defined so far. Permafrost (without seasonally frozen ground) is also considered in the category 'Hydrology' with different requirements, e.g. ranging from 0.1 to 100 km spatial resolution. Timeliness is defined in the same order as observation frequency in the OSCAR database.

3.4 Permafrost_cci specific user requirements survey

An additional survey has been setup within permafrost_cci to capture the needs of so far identified dedicated case studies as well as extended climate modelling requirements. Application cases include also mountain permafrost (PERMOS and Carpathian) and Arctic coastal erosion (HORIZON2020 Nunataryuk) monitoring.

At least two levels of requirement should be identified:

- Threshold requirement: the limit at which the observation becomes ineffectual and is not of use for the climate-related application.
- Target requirement: the maximum performance limit for the observation, beyond which no significant improvement would result for climate applications. Threshold and target requirements have been determined for ground temperature as well as active layer thickness. Results are summarized in *Table 3* and *Table 4*.

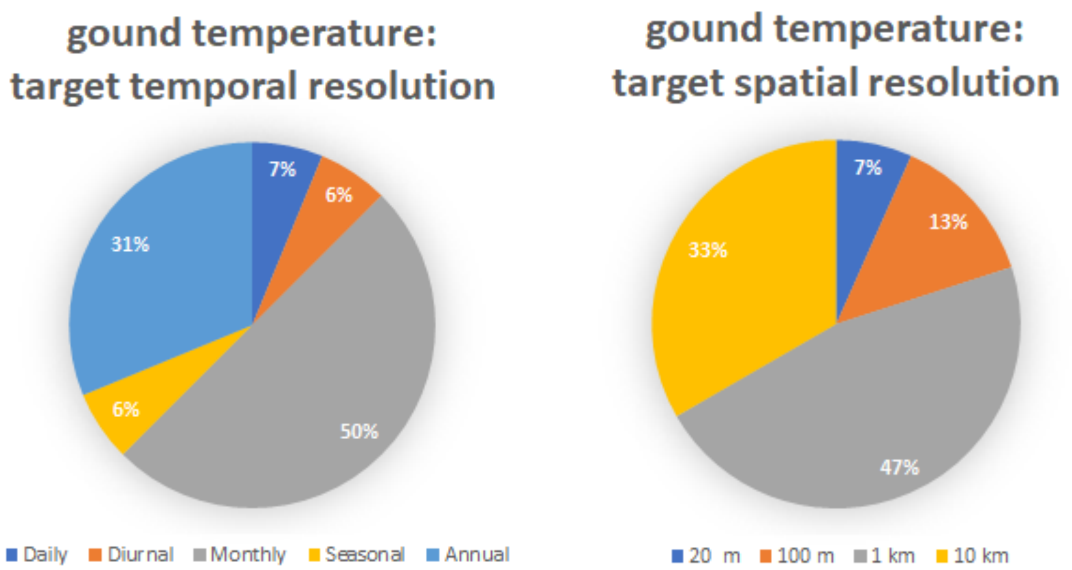

Figure 3: Permafrost_cci specific user requirements survey results for ground temperature temporal and spatial resolution (target)

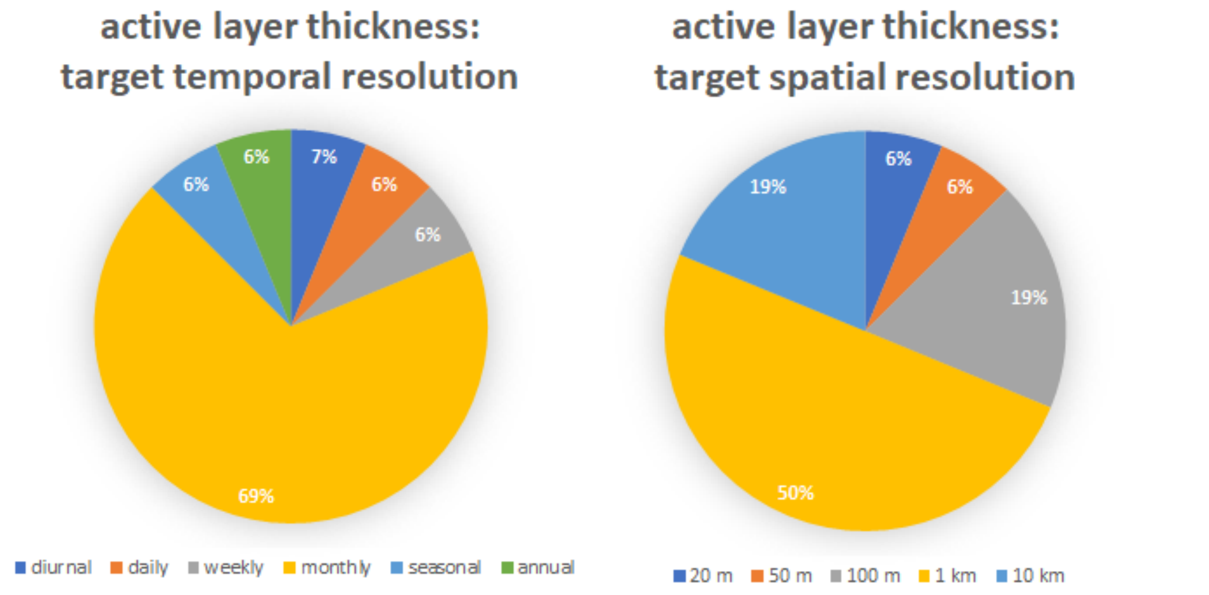

Figure 4: Permafrost_cci specific user requirements survey results for active layer thickness temporal and spatial resolution (target)

9 out of 16 respondents would use the permafrost_cci datasets for validation of models:

- Five responses have been received for climate/landsurface modelling applications, including JULES, CLM, RASM
- Three respondents work on applications with similar permafrost modelling approaches as foreseen in Permafrost_cci (Cryogrid, mechanical properties of frozen soils)

Five further respondents plan application of the dataset in Arctic regions including quantification of carbon fluxes from land to ocean, interpretation of long-term change of landsurface features and Anthrax risk modelling.

As threshold, five respondents ask for global coverage, and eleven for pan-Arctic in case of ground temperature. The need for global coverage increases to 50% for target requirement. This request comes especially from climate/landsurface modelling applications. A threshold accuracy of RMSE<2.5K for ground temperature and <25cm for ALT is requested for climate modelling use cases foreseen within permafrost_cci. Spatial and temporal resolution requirements are similar for ground temperature and active layer thickness. The majority of respondents requires 1km spatial resolution at monthly intervals (target; Figure 3 and Figure 4), confirming results of the GlobPermafrost user survey [RD-1].

88% of the respondents see sub-grid scale representation of temperature variability desirable for target requirements. For mountain permafrost it is suggested to set different accuracy requirements depending on temperature (e.g. near 0°C RMSE <0.1K, lower than -3°C RMSE<0.5K).

Table 3: Threshold (minimum) and target (optimal) requirements identified for ground temperatures [URq_12]

	Threshold requirement	Target requirement
	Coverage and sampling	
Geographical coverage	Pan-Arctic	Global with regional specific products
Temporal sampling	annually	monthly
Temporal extent	Last decade	1979 - present
	Resolution	
Horizontal resolution	10 km	1km
Subgrid variability	no	yes
Vertical resolution	50 cm exponential	5 cm exponential
Vertical extent	15 m	30 m
	Error/Uncertainty	
Precision	0.5 K	0.1 K
Accuracy	RMSE < 2.5°C	RMSE < 0.5°C
Stability	Higher stability than existing datasets	Accuracy needs to be temporally homogeneous
Error characteristics	Independent multi-date validation	Independent multi-date validation

Table 4: Threshold (minimum) and target (optimal) requirements identified for active layer thickness [URq_13]

	Threshold requirement	Target requirement
	Coverage and sampling	
Geographical coverage	Pan-Arctic	Global with regional specific products
Temporal sampling	< yearly	< monthly
Temporal extent	Last decade	1979 - present
	Resolution	
Horizontal resolution	10 km	1km
	Error/Uncertainty	
Precision	10 cm	1 cm
Accuracy	RMSE < 25 cm	RMSE < 10 cm
Stability	Accuracy needs to be temporally homogeneous	Accuracy needs to be temporally homogeneous
Error characteristics	Independent multi-date validation	Independent multi-date validation

3.5 Further climate and permafrost modelling requirements

Interviews with climate modellers and permafrost specialists have been carried out in addition to the online survey of ESA DUE GlobPermafrost in 2016. It has been pointed out that a new ground stratigraphy product for the permafrost domain needs to be compiled in close consultation with climate modelers [URq_10]. It is consensus in the community that currently existing classifications are heavily flawed for permafrost so that such a product has been sought after by the community by a long time and is still not available to date.

In general, NetCDF is a basic requirement for climate modelling, including CMUG [URq_10]. Obs4MIPs (Observations for Model Intercomparisons Project) is an activity to make observational products more accessible for climate model intercomparisons via the same searchable distributed system used to serve and disseminate the rapidly expanding set of simulations made available for community research. In obs4MIPs usually monthly means are required [URq_14]. Permafrost specific parameters which are currently registered for CMIP are Permafrost Layer Thickness (tpf) and Liquid Water Content of Permafrost Layer (pflw). These parameters are not feasible for monitoring with satellite data and are therefor not further considered.
The Climate Modelling User Group (CMUG) is tasked with updating the Climate Monitoring Facility (CMF) database and providing a toolbox application to allow interrogation of the ECV data held on the Climate Data Store (CDS). Stable datasets in NetCDF format with one product per file are required [URq_15]. Monthly means and daily data would be desirable for each variable [URq_16], at the ERA5 spatial resolution (0.25°x0.25°) [URq_17]. The CMIP6 comparison with the ESA DUE GlobPermafrost dataset for permafrost extent by Burke et al. (2020) has been made at 0.5°x0.5°. The comparison time period for ground temperature was 1995-2014. A temporal overlap could not be archived in this case but would be desired. This is in line with requirements collected in the Permafrost_cci user survey [URq_12].

4 USER REQUIREMENTS FEASIBILITY

User requirements as summarized in Tables 1 and 2 go considerably beyond the state-of-the-art in remote permafrost ECV assessment, based on published studies and recently demonstrated progress. Essentially, users demand [URq_09,12,13] a combination of

1. Extensive geographical coverage (global permafrost extent 20-30 Mio km^2); High spatial resolution (target resolution 1km), including representation of subgrid variability;
2. High temporal resolution (monthly data);
3. Long temporal coverage (one to several decades back in time).

Since the permafrost ECV cannot be directly characterized from space-borne remote sensors, all published methods rely on a transfer function or model in order to obtain ECV information from one or several sources of remote sensing data. Therefore, both the model/transfer function and the input satellite data sets must be assessed when evaluating suitability to fulfil user requirements. In the ESA GlobPermafrost project, for example, a simple equilibrium model has been employed to compute ground temperatures and thus infer permafrost presence at 1km spatial resolution (Westermann et al., 2015, Obu et al., in review). Although the input satellite data sets feature a high temporal resolution, e.g. diurnal for Land Surface Temperature, the employed model limits the final temporal resolution to a decade or longer, which would not fulfil threshold requirements stated by most users. Algorithm selection in Permafrost_cci must therefore closely consider the interplay between satellite data and employed model scheme.

Accuracy requirements stated by the users are strongly complicated by the fact that permafrost ECV physical variables (ground temperature and active layer thickness) often feature significant variations at spatial scales below the target requirement of 1km, which in the few documented cases (see below) exceed even the threshold requirement of an RMSE of 2.5K (e.g. Fig. 2 in Gisnås et al, 2014). Therefore, even comparison of “perfect” 1km average temperatures to point temperature measurements in boreholes will feature a significant RMSE which in this case rather reflects the spread of temperatures in space than the accuracy of the method (assuming that boreholes are placed at random locations within a pixel). In real-world permafrost ECV assessment, a bias introduced by the method/model and the input data will overlap with this effect, which significantly complicates the evaluation of accuracies. A straight-forward method to overcome this difficulty would be to increase the spatial resolution until the method can indeed deliver the deterministic temperature at the locations of individual boreholes. However, this would require a pixel resolution of about 10m, which is several orders of magnitude smaller than what has been demonstrated in published studies. The very high accuracy requested in GCOS-200 as well as GCOS-245 [AD-6]from in situ measurements is therefore not achievable in case of modelling based on satellite data records.

The challenge for permafrost fraction assessment is the poor availability of in-situ data for PF fraction at 1km scale (see Chadburn et al., 2017). A practical method to provide uncertainty estimates at the pixel/grid level is required. Chadburn et al. (2017) suggest the use of high resolution land cover with its classes as proxy for permafrost distribution in the transition zone. Such approaches have recently

been tested also for medium resolution data (Landsat, Cable et al. 2016) and C-band SAR, see also Bartsch et al. (2016).
Another way of overcoming these challenges would be to measure ECV physical variables not only at single points (as it is e.g. done in the GTN-P network), but assess the full spatial distribution or at least the magnitude of the spread with spatially distributed logger arrays. In the last years, such arrays have been installed at a few sites (e.g. Ny-Ålesund, Svalbard, peat plateaus N Norway, S. Westermann; mountain sites S Norway, K. Gisnås; Terelj National Park, Mongolia, D. Arvimed; Trail Valley creek, Canada, J. Boike; near Yellowknife, Canada, S. Gruber; Kaldoaivi, Finland, A. Bartsch), but the number of sites is not sufficient to validate a global model. Furthermore, only a few years (max. 6 years for Ny-Ålesund) are available and often only ground surface temperature, which does not fully reflect the effect of seasonally different heat transfer in the active layer (the so-called thermal offset) on permafrost temperatures. In conclusion, user requirements on accuracy must be developed further in Permafrost_cci together with the users most of who have already stated "representation of subgrid variability" as a requirement.

WMO OSCAR high-resolution temporal resolution requirements [URq_09] might relate to the velocity of atmospheric processes and so to the drivers in modelling or the dynamics of seasonally frozen soil (e.g., to account for the number of freezing and thawing days). However, permafrost is a sub-surface property and the relationships between the frozen ground and the relevant climatic elements, are complex. These OSCAR requirements have been so far not confirmed in published user surveys regarding permafrost.

URq_05/06: The process of standardization of borehole records via GTN-P is not yet completed. Within the GCOS GTN-P data collection up to date from 1360 boreholes only 369 boreholes contain in addition to the metadata entries also the in-situ datasets. Data from 305 GTN-P boreholes (including mountain permafrost boreholes) are usable. Before the production of consistent time depth series from the GTN-P data base the usable data need to be screened for outlier and noise that would have an impact on the averaging and exist in some of the datasets. There are also some accuracy issues related to the correct geolocation of boreholes. Some coordinates have been identified to be within rivers, lakes or the sea. Checking each borehole by hand and if necessary correct coordinates is now ongoing in contacting data authors, providers and NSIDC about the correct geolocation. Since the start of Permafrost_cci, already the half of the incorrect borehole locations could be adapted with the help of data authors/providers. Several PIs (e-g., China with a share of around 200 boreholes) have up to date not submitted GTN-P borehole data to the IPA/GTN-P data portal. The GTN-P office is currently supporting borehole data intake into the GTN-P data portal.

The consistency of the products of the other CCI and CCI+ products will be crucial for the consistency that can be provided by Permafrost_cci.

5 SUMMARY

All specific user requirements are listed in Table 5. It provides a summary of the identified user requirements that is organised by EO data product. 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 annual cycle, taking into account data availability and workload constraints.

Table 5: Summary of user requirements. Background (BG) means that this is a continuous activity, production (P), and dissemination (D) means that the related requirement has to be considered during production, and dissemination, respectively. Parameters are Permafrost Extent (PE), Ground Temperature (GT) and Active Layer Thickness (ALT).

ID	Parameter	Requirements	Source	Type
URq_01	PE/GT/ALT	higher spatial resolution than a map scale of 1:10,000,000	IPA Mapping group report	BG
URq_02	PE/GT/ALT	data need to be related to a time stamp	IPA Mapping group report	P
URq_03	PE/GT/ALT	form of delivery for maps and data need to be flexible	IPA Mapping group report	D
URq_04	PE/GT/ALT	high data quality	IPA Mapping group report	BG
URq_05	PE/GT/ALT	benchmark dataset needs to be developed	IPA Mapping group report, GlobPermafrost/IPA mapping group workshop	P
URq_06	PE/GT/ALT	evaluation through community	GlobPermafrost/IPA mapping group workshop	P
URq_07	PE/GT/ALT	terminology for modelling output 'potential'	GlobPermafrost/IPA mapping group workshop	D
URq_08	GT/ALT	depth of active layer, permafrost temperature in K and seasonal soil freeze/thaw needs to be addressed	GCOS	BG
URq_09	PE	Threshold: uncertainty 10-25%, hor. res. 10-100 km, temp. res. 3-5 days, timeliness 5-6 days; breakthrough uncertainty 7-8.5%, hor. res. 0.85 - 1 km, temp. res. 14-36 hours, timeliness 14-36 h	OSCAR	BG
URq_10	PE/GT/ALT	Distribution as NetCDF	CMUG	D
URq_11	PE/GT/ALT	Development of a new ground stratigraphy product for the permafrost domain	GlobPermafrost survey	P/D
URq_12	GT	Threshold: pan-arctic, yearly, last decade, 10km, RMSE<2.5°C; Target: global, monthly, 1979-present, 1km, subgrid variability, RMSE < 0.5°C	Permafrost_cci survey	BG
URq_13	ALT	Threshold: pan-arctic, yearly, last decade, 10km, RMSE<25cm; Target: global, monthly, 1979-present, 1km, subgrid variability, RMSE<10cm	Permafrost_cci survey	BG
URq_14	PE/GT/ALT	Monthly products	CMUG/ obs4MIPs	P

URq_15	PE/GT/ALT	NetCDF format with one product per file	CMUG/Climate Data Store (CDS)	D
URq_16	PE/GT/ALT	Monthly means and daily data	CMUG/Climate Data Store (CDS)	P
URq_17	PE/GT/ALT	ERA5 spatial resolution (0.25°x0.25°)	CMUG/Climate Data Store (CDS)	P
URq_18	PE	Threshold: global, yearly, 1m, 95%; Target: global, 10-years, 100m, 85%	User Requirements for a Copernicus Polar Mission	BG
URq_19	ALT	Threshold RMSE 2/15cm, goal RMSE 1/5 cm (mechanical probing penetration uncertainty/ sensor uncertainty)	GCOS	BG

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6.2 Acronyms

ACOP	Asian Conference on Permafrost
ALT	Active Layer Thickness
Arctic CORDEX	Coordinated Regional Climate Downscaling Experiment
AWI	Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research
B.GEOS	b.geos GmbH
CALM	Circumpolar Active Layer Monitoring
CliC	Climate and Cryosphere project
CLM4	Land Community Model
CCI	Climate Change Initiative
CMIP-6	The Coupled Model Intercomparison Project
CMUG	Climate Modelling User Group
CRESCENDO	Coordinated Research in Earth Systems and Climate: Experiments, Knowledge, Dissemination and Outreach
CRG	Climate Research Group
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
ESA DUE	ESA Data User Element
GAMMA	Gamma Remote Sensing AG

GCOS	Global Climate Observing System
GCW	Global Cryosphere Watch
GT	Ground Temperature
GTN-P	Global Terrestrial Network for Permafrost
GTOS	Global Terrestrial Observing System
GUIO	Department of Geosciences University of Oslo
HIRHAM	High Resolution Limited Area Model
IASC	International Arctic Science Committee
ILAMB	International Land Model Benchmarking
IPA	International Permafrost Association
IPCC	Intergovernmental Panel on Climate Change
LS3MIP	Land Surface, Snow and Soil Moisture
MAGT	Mean Annual Ground Temperature
NetCDF	Network Common Data Format
NSIDC	National Snow and Ice Data Center
PCN	Permafrost Carbon Network
PE	Permafrost Extent
PERMOS	Swiss Permafrost Monitoring Network
PF	Permafrost
PSTG	Polar Space Task Group
RASM	Regional Arctic System Model
RD	Reference Document
RMSE	Root Mean Square Error
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SCAR	Scientific Committee on Antarctic Research
SU	Department of Physical Geography Stockholm University
TSP	Thermal State of Permafrost
UNIFR	Department of Geosciences University of Fribourg
URD	Users Requirement Document
WCRP	World Climate Research Program
WMO	World Meteorological Organisation
WMO OSCAR	Observing Systems Capability Analysis and Review Tool
WUT	West University of Timisoara