permafrost
cci

CCI+ PHASE 2 – NEW ECVS
PERMAFROST

D1.2 PRODUCT SPECIFICATIONS DOCUMENT (PSD)

VERSION 4.0

15 FEBRUARY 2023

PREPARED BY

b·geos

GAMMA REMOTE SENSING

UiO : University of Oslo

AWI

UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

Stockholm University

West University of Timisoara

TERRASIGNA

NORCE

UNIS
The University Centre in Svalbard

Document Status Sheet

Issue	Date	Details	Authors
1.0	15.01.2019	First version	AB, CK (B.GEOS), TS, AW (GAMMA), SW (UIO)
2.0	30.11.2019	Version 2, update of file names, meta-data, validation data sources and product accuracy	AB (B.GEOS)
3.0	30.11.2020	Version 3, update of file names, meta-data and reference list	AB (B.GEOS)
4.0	15.02.2023	Updates, first iteration phase 2, considering CMUG feedback (details on spin-up), latest validation results	SW (UIO), AB (B.GEOS), BH, MW (AWI)

Author team

Annett Bartsch, B.GEOS

Sebastian Westermann, UIO

Tazio Strozzi, GAMMA

Andreas Wiesmann, GAMMA

Christine Kroisleitner, BGEOS

Mareike Wieczorek, AWI

Birgit Heim, AWI

ESA Technical Officer:
Frank Martin Seifert

EUROPEAN SPACE AGENCY CONTRACT REPORT

The work described in this report was done under ESA contract. Responsibility for the contents resides in the authors or organizations that prepared it.

TABLE OF CONTENTS

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 are elaborated during Phase 1 of CCI+ (2018-2021) and continued during Phase 2 of CCI+ (2022-2025).

This document is the Permafrost_cci Product Specification Document (PSD) corresponding to the iteration 1 dataset of Phase 2 of the Permafrost_cci project. It describes the product specifications of the Permafrost products. The product specifications address the main requirements expressed by the users in the User Requirements Document (URDv3.0, RD-3) including those expressed by the Permafrost_cci climate research group (CRG). Since the range of potential user communities of a Permafrost product is very wide it is not possible to cover all those requirements. For this reason, the PSD establishes priorities between those requirements, putting in the first place those more sensible to climate researchers, while considering current technical constraints.

The PSD includes a glossary of permafrost relevant terms, the product specifications and formats, including details of meta data.

Ground temperature and active layer thickness are considered the primary variables that require climate-standard continuity as defined by GCOS. Permafrost fraction and zone are secondary parameters, but of high interest to users. Annual averages of ground temperature and annual maxima of thaw depth (active layer thickness) are provided at 1km spatial resolution during phase 1 as well as phase 2 of Permafrost_cci. Product level is 4. The data sets are created from the analysis of lower level data, resulting in gridded, gap-free products.

1 INTRODUCTION

1.1 Purpose of the document

This document describes in detail product specifications in order to obtain a permafrost product that is consistent, stable and error-characterised. The purpose of this document is to present the structure, syntax and file naming conventions used to describe the different permafrost products. It provides all the necessary data needed by permafrost algorithm developers and users to write and read the permafrost products respectively.

1.2 Structure of the document

This document contains a glossary of permafrost specific terms in section 1.7. Section 2 describes the area covered for the service as well as regions of interest for evaluation. The remaining sections detail the product specifications and format.

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] CMUG (2022): CCI+ Deliverable D2.3: Suitability of CCI ECVs for Climate Science and Services. v3.0

[AD-6] GCOS-244, The 2022 GCOS Implementation Plan. 2022.

[AD-7] GCOS-245, The 2022 GCOS ECV requirements. 2022.

1.4 Reference Documents

[RD-1] 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-2] Bartsch, A., Westermann, S., Heim, B., Wieczorek, M., Pellet, C., Barboux, C., Kroisleitner, C., Strozzi, T. (2019): ESA CCI+ Permafrost Data Access Requirements Document, v1.0

[RD-3] Bartsch, A., Matthes, H., Westermann, S., Heim, B., Pellet, C., Onacu, A., Kroisleitner, C., Strozzi, T. (2019): ESA CCI+ Permafrost User Requirements Document, v3.0

[RD-4] Westermann, S. Bartsch, A., Strozzi, T. (2019): ESA CCI+D2.1 Product Validation Algorithm Selection Report (PVASR). V1.0

[RD-5] Heim, B., Wieczorek, M., Pellet, C., Barboux, C., Delaloye, R., Bartsch, A., Strozzi, T. (2019): ESA CCI+ PVIR, v1.0

[RD-6] Heim, B., Wieczorek, M., Pellet, C., Delaloye, R., Bartsch, A., Strozzi, T. (2020): ESA CCI+ D.4.1 Product validation and intercomparison report (PVIR), v2.0

[RD-7] Heim, B., Lisovski, S., Wieczorek, M., Pellet, C., Delaloye, R., Bartsch, A., Jakober, D., Pointer, G., Strozzi, T. (2021): ESA CCI+ D.4.1 Product validation and intercomparison report (PVIR), v3.0

[RD-8] Bartsch, A., Westermann, S., Heim, B., Wieczorek, M., Pellet, C., Barboux, C., Delaloye, R., Kroisleitner, C., Strozzi, T. (2020): ESA CCI+ Permafrost Data Access Requirements Document, v2.0

1.5 Bibliography

A complete bibliographic list that supports arguments or statements made within the current document is provided in Section 5.1.

1.6 Acronyms

A list of acronyms is provided in section 5.2.

1.7 Glossary

The list below provides a selection of terms relevant for the parameters addressed in Permafrost_cci [RD-1].

active layer

The layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost. In the zone of continuous permafrost the active layer generally reaches the permafrost table; in the zone of discontinuous permafrost it often does not. 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).

The active layer is sometimes referred to as the "active zone"; the term "zone," however, should be reserved for the zones of discontinuous and continuous permafrost.

In Russian and Chinese literature, the term active layer covers two distinct types: (1) the seasonally thawed layer overlying permafrost, and (2) the seasonally frozen layer overlying unfrozen ground inside or outside permafrost areas.

REFERENCES: Muller, 1943; Williams, 1965; Brown, 1971; van Everdingen, 1985.

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 content, 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.

continuous permafrost zone

The major subdivision of a permafrost region in which permafrost occurs everywhere beneath the exposed land surface with the exception of widely scattered sites.

Taliks associated with rivers and lakes may occur in the continuous permafrost zone.

REFERENCE: Brown, 1970.

depth of zero annual amplitude

The distance from the ground surface downward to the level beneath which there is practically no annual fluctuation in ground temperature .

A change of no more than 0.1°C throughout the year is arbitrarily considered as "practically no annual fluctuation". The temperature at the depth (or level) of zero annual amplitude ranges from about -0.1°C at the southern limit of the permafrost region to about -15°C in the extreme polar reaches of the zone of continuous permafrost. The depth of zero annual amplitude varies widely but generally lies between 10 and 20 m below the ground surface, depending on climatic and terrain conditions such as amplitude of annual surface temperature variation, vegetation, snowcover and characteristics of the soils and rocks including thermal diffusivity (see thermal properties of frozen ground).

SYNONYMS: (not recommended) zone of minimum annual amplitude, zone of zero annual amplitude.

REFERENCE: Muller, 1943.

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.

discontinuous permafrost zone

The major subdivision of a permafrost region in which permafrost occurs in some areas beneath the exposed land surface, whereas other areas are free of permafrost.

The zone of discontinuous permafrost lies between the continuous permafrost zone and the southern latitudinal limit of permafrost in lowlands. Near its northern boundary, discontinuous permafrost is extensive, where-as near its southern boundary it occurs as isolated patches of permafrost, and sporadic permafrost. There is no sharp distinction, or boundary, between the continuous and discontinuous permafrost zones.

REFERENCE: Brown, 1970.

disequilibrium permafrost

Permafrost that is not in thermal equilibrium with the existing mean annual surface or sea-bottom temperature and the geothermal heat flux.
REFERENCE: Mackay, 1972a.

equilibrium permafrost

Permafrost that is in thermal equilibrium with the existing mean annual surface or sea-bottom temperature and with the geothermal heat flux.
SYNONYM: contemporary permafrost.
REFERENCE: Mackay, 1972a.

extensive discontinuous permafrost

1. (North-American usage) Permafrost underlying 65 to 90 percent of the area of exposed land surface.
2. (Russian usage) Permafrost underlying 70 to 80 percent of the area of exposed land surface.
It is suggested that this term be used as a replacement for "widespread" discontinuous permafrost, because the word "widespread" can mean either "extensively distributed" or "widely spaced".
SYNONYM: widespread discontinuous permafrost.
REFERENCE: Heginbottom and Radburn, 1992.

ground ice

A general term referring to all types of ice contained in freezing and frozen ground .
Ground ice occurs in pores, cavities, voids or other openings in soil or rock and includes massive ice. It generally excludes buried ice, except in Russian usage. Ground ice may be epigenetic or syngenetic, contemporaneous or relict, aggrading or degrading, perennial or seasonal. It may occur as lenses, wedges, veins, sheets, seams, irregular masses, or as individual crystals or coatings on mineral or organic particles. Perennial ground ice can only occur within permafrost bodies.
REFERENCES: Mackay, 1972b; Pollard and French, 1980.

ice content

The amount of ice contained in frozen or partially frozen soil or rock.
Ice content is normally expressed in one of two ways:
1. on a dry-weight basis (gravimetric), as the ratio of the mass of the ice in a sample to the mass of the dry sample, expressed as a percentage, or
2. on a volume basis (volumetric), as the ratio of the volume of ice in a sample to the volume of the whole sample, expressed as a fraction.
The volumetric ice content cannot exceed unity whereas the gravimetric ice content can greatly exceed 100 percent.
REFERENCES: Penner, 1970; Anderson and Morgenstern, 1973; Johnston, 1981.

isolated patches of permafrost

Permafrost underlying less than 10 percent of the exposed land sur-face.
Individual areas of permafrost are of limited areal extent, widely separated, and are completely surrounded by unfrozen ground.

SYNONYMS: (not recommended) insular permafrost; island perma-frost; scattered permafrost.
REFERENCES: Heginbottom and Radburn, 1992.

mean annual ground-surface temperature (MAGST)

Mean annual temperature of the surface of the ground.
Permafrost exists if the mean annual ground-surface temperature is perennially below 0°C. Although the mean annual surface temperature may be below 0°C, the surface temperature will fluctuate during the year, causing a layer of ground immediately beneath the surface to thaw in the summer and freeze in the winter (the active layer). Small changes in the annual range of surface temperature and in the mean annual surface temperature from year to year, or over a period of a few years, may cause a layer of ground between the bottom of the active layer and the permafrost table to remain at a temperature above 0°C, creating a talik or residual thaw layer. [RD-1]

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-1]

n-factor

The ratio of the surface freezing or thawing index to the air freezing or thawing index.
At any site, (standard) air temperatures are seldom the same as surface (air/substrate boundary) temperatures. Because air temperatures (measured at weather stations) are usually available and surface temperatures are not, the n-factor (an empirically determined coefficient) is used to relate air temperatures to surface temperatures in order to establish the thermal boundary condition at the surface, particularly for engineering purposes.
The difference between air and surface temperatures at any specific time and location is greatly influenced by climatic, surface and subsurface conditions (e.g., latitude, cloud cover, time of day or year, relative humidity, wind speed, type of surface--wet, dry, moss, snow, natural vegetated te-rain, mineral soil, pavements-- and thermal properties of the ground). The average surface temperature and n-factor may vary significantly from year to year, even for a given surface and location, as well as for different sites, surfaces and soil systems.
Values of the freezing and thawing n-factors have been determined for a large number of sites and surfaces and are widely used for predicting sur-face temperatures and the thermal regime of the ground. The data vary widely, however, and indicate that a rigorous value of n for a given site cannot simply be chosen from these data. Direct determination of the n-factor for a specific location is much better and requires concurrent observations of air and surface temperatures throughout at least one and prefer-ably several complete freezing and thawing seasons.
REFERENCES: Carlson and Kersten, 1953; Lunardini, 1978, 1981.

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 pipelines, 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.

permafrost boundary

1. The geographical boundary between the continuous and discontinuous permafrost zones.
2. The margin of a discrete body of permafrost.

permafrost degradation

A naturally or artificially caused decrease in the thickness and/or areal extent of permafrost.

Permafrost degradation may be caused by climatic warming or by changes in terrain conditions, such as disturbance or removal of an insulating vegetation layer by fire, or by flooding caused by a landslide-blocked stream, or by human activity. It may be expressed as a thickening of the active layer, a lowering of the permafrost table, a raising of the permafrost base, or a reduction in the areal extent or the complete disappearance of permafrost. [RD-1]

permafrost region

A region in which the temperature of some or all of the ground be-low the seasonally freezing and thawing layer remains continuously at or below 0°C for at least two consecutive years.

The permafrost region is commonly subdivided into permafrost zones. [RD-1]

permafrost zone

A major subdivision of a permafrost region.

A permafrost region is commonly subdivided into permafrost zones based on the proportion of the ground that is perennially cryotic. The basic subdivision in high latitudes is into zones of continuous permafrost and discontinuous permafrost.

REFERENCES: Muller, 1943; Brown, 1967, 1978; Washburn, 1979; Pewe, 1983.

sporadic discontinuous permafrost

1. (North-American usage) Permafrost underlying 10 to 35 percent of the exposed land surface.

2. (Russian usage) Permafrost underlying 5 to 30 percent of the exposed land surface.
Individual areas of permafrost are completely surrounded by unfrozen ground.
SYNONYMS: (not recommended) insular permafrost; island perma-frost; scattered permafrost.
REFERENCES: Muller, 1943; Brown, 1967; Heginbottom and Radburn, 1992.

talik

A layer or body of unfrozen ground occurring in a permafrost area due to a local anomaly in thermal, hydrological, hydrogeological, or hydrochemical conditions .
Taliks may have temperatures above 0°C (noncryotic) or below 0°C (cryotic, forming part of the permafrost). Some taliks may be affected by seasonal freezing. Several types of taliks can be distinguished on the basis of their relationship to the permafrost (closed, open, lateral, isolated and transient taliks), and on the basis of the mechanism responsible for their unfrozen condition (hydrochemical, hydrothermal and thermal taliks):
1. closed talik - a noncryotic talik occupying a depression in the perma-frost table below a lake or river (also called "lake talik" and "river talik"); its temperature remains above 0°C because of the heat storage effect of the surface water;
2. hydrochemical talik - a cryotic talik in which freezing is prevented by mineralized groundwater flowing through the talik.
3. hydrothermal talik - a noncryotic talik, the temperature of which is maintained above 0□°C by the heat supplied by groundwater flowing through the talik;
4. isolated talik - a talik entirely surrounded by perennially frozen ground; usually cryotic (see isolated cryopeg), but may be noncryotic (see transient talik);
5. lateral talik - a talik overlain and underlain by perennially frozen ground; can be noncryotic or cryotic;
6. open talik - a talik that penetrates the permafrost completely, con-necting suprapermafrost and subpermafrost water, (e.g., below large rivers and lakes).
It may be noncryotic (see hydrothermal talik) or cryotic (see hydro-chemical talik).
SYNONYMS: (not recommended) through talik, penetrating talik, perforating talik, piercing talik;
7. thermal talik - a noncryotic talik, the temperature of which is above 0°C due to the local thermal regime of the ground;
8. transient talik - a talik that is gradually being eliminated by freezing, e.g., the initially noncryotic closed talik below a small lake which, upon draining of the lake, is turned into a transient isolated talik by permafrost aggradation (see also closed-system pingo).
REFERENCES: Williams, 1965; Washburn, 1973; van Everdingen, 1976.

2 KEY REGIONS FOR STUDY

2.1 Global Permafrost distribution

Permafrost is a phenomenon of the subsurface thermal state across vast areas. Permafrost underlies approx. 24% of the terrestrial Northern Hemisphere (Figure 1). Southern hemisphere permafrost occurs in the Andean mountains, in the Southern Alps in New Zealand and ice-free areas of the Antarctic content and neighbouring islands. All regions where permafrost can occur will be covered in Permafrost_cci.

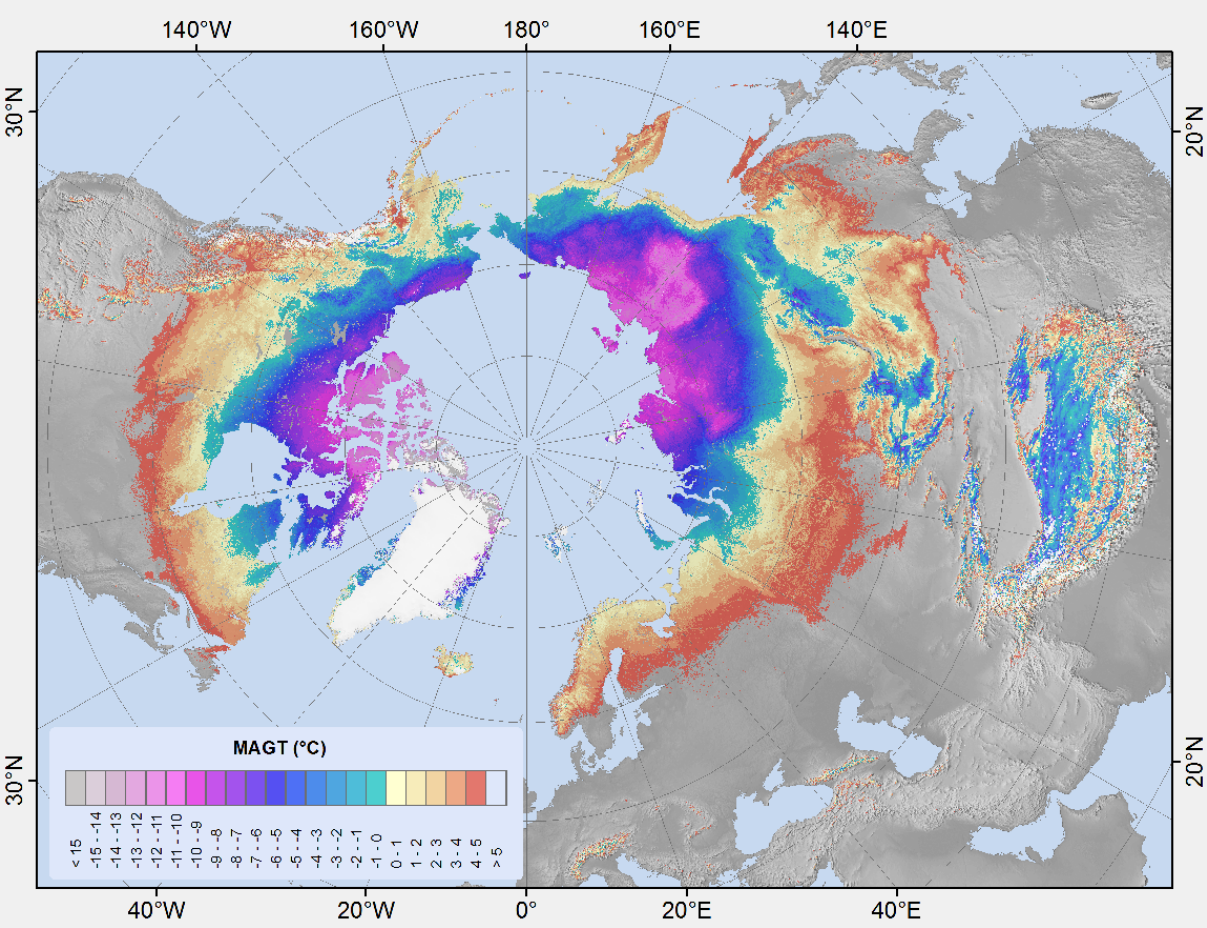

Figure 1: Modelled Mean Annual Ground temperature (MAGT) in regions with permafrost probability larger than zero (GlobPermafrost). Data: Obu et al., 2018, 2019

2.2 Regions for evaluation

The validation is carried out independently from the algorithm development team and uses the WMO Global Terrestrial Network for Permafrost (GTN-P), also specifically the mountain permafrost monitoring program PERMOS in Switzerland and additional international and national ground monitoring programs, e.g., Roshydromet RHM, and from data repositories: the Canadian data repository for Polar research Nordicana-D (http://www.cen.ulaval.ca/nordicanad/dpage.aspx?doi=45291SL34F28A9491014AFD), the German data repository for Earth and Environment, PANGAEA, the US Arctic Data Centre, and the NASA ARCTIC-BOREAL VULNERABILITY EXPERIMENT ABOVE

https://above.nasa.gov/field_data_products.html) for validation throughout the project. All available maps and data are documented in the Data Access Requirements Document (DARD, [RD-2], [RD-8]).Especially GTN-P borehole sites in Alaska are investigated in comparison to GIPL2 runs (Dmitry Nicolsky, University of Alaska Fairbanks, USA) and the ESA DUE GlobPermafrost map (equilibrium model) for benchmarking [RD-4, RD-5]. Further regional comparisons are made for mountain regions in the European Alps (e.g., PERMOS). Evaluation also considers rock glacier inventories where available [RD-6].

3 PRODUCTS SPECIFICATIONS

3.1 Ground temperatures, active layer thickness and permafrost fractions

3.1.1 Product description

This product includes the ECV state variables ground temperature and active layer thickness, derived from a thermal model driven and constrained by EO data. In addition, the product provides a yearly fraction of permafrost-underlain and permafrost-free area within a pixel, as well as the areal fraction underlain by a talik (permafrost-free zone on top of degrading permafrost, which is the result of near-surface permafrost degradation). Classification according to the IPA permafrost map delivers the well-known permafrost zones, distinguishing sporadic, discontinuous and continuous permafrost. The model spin-up largely follows the accelerated spin-up procedure described in Westermann et al., (2022), Sect. 3.1.4. While the main transient model run starts in the year 1980, the deeper parts of the vertical temperature profile are initialized to reflect climate conditions in the period 1950 to 1979, the first thirty-year period for which the ERA5 reanalysis is available. To ensure that the near-surface temperature cycle is independent of the initial conditions, transient simulations from 1980 to 1996 are conducted before processing the "Permafrost_CCI product years" 1997 to 2021.

3.1.2 Temporal compositing

The temporal resolution is one year, which corresponds to average Mean Annual Ground Temperature (MAGT), as well as the maximum depth of seasonal thaw, which corresponds to the active layer thickness (ALT).

3.1.3 Spatial resolution

The spatial resolution of the Permafrost_CCI products will be linked to the best available resolution of the input sensor. Here, the spatial resolution is limited to 1km, which is the spatial resolution of remotely sensed LST. However, we apply ensemble-based modelling of subpixel variability, i.e. different ensemble members represent different ground stratigraphies and snow depths found within 1km pixels. This is required for computation of permafrost and talik fractions.

3.1.4 Pixel attributes

ECV variable	unit	property	values provided	Product string
ground temperature at certain depth (maximum 5 m)	degree C	annual average	median and standard deviation of the ensemble	GTD
active layer thickness	m	annual maximum	median and standard deviation of the ensemble	ALT

permafrost fraction	0-1	annual minimum		PFR
permafrost-free fraction	0-1	annual maximum		PFF
fraction underlain by talik	0-1	difference of the above		PFT
permafrost zone	four classes: no permafrost or isola-ted, sporadic, discon-tinuous, continuous			PZO

3.2 Product accuracy

With respect to the threshold user requirements documented in [RD-3] the following accuracy is targeted in year 2/3 of phase 1:

- Ground temperature: 2.0 degree C compared to GTN-P boreholes
- Active layer thickness: RMSE <0.25m for ALT < 1.0 m and RMSE <0.5 m for ALT >1.0 m

Product accuracy of phase 1/ year 1 dataset is documented in [RD-5], of year 2 dataset in [RD-6]. The accuracy of V3.0, CRDP V2 (phase 1, year 3) is documented in [RD-7] and demonstrates for Mean Annual Ground Temperature (MAGT) time series from 1997 to 2019 across all depths an absolute bias of 1.58 °C, a mean bias of 0.98 °C and an RMSE of 1.93 °C for the whole range of validation data. Considering only permafrost measurement borehole sites with an MAGT <1 °C, we get an absolute bias of 1.46 °C, a mean bias of -0.01 °C and an RMSE of 1.87 °C. Geographically, the extreme residuals showed no obvious spatial clusters. However, a relatively large proportion of residuals >95% quantile were located across Alaska, specifically in the boreal region. Residuals across depths varied around zero, without notable differences in the median bias.

Active layer thickness of the V3.0, CRDP V2 (phase 1, year 3) is characterized by an absolute bias of 30 cm, a mean bias of -1.08 cm and an RMSE of 47 cm, when calculated for the bulk dataset (excluding sites in China and Mongolia that represent high altitude permafrost site with very coarsely measured deep active layer measurements deduced from temperature sensors).

3.3 Data dissemination for all products

All CCI map time series are distributed via the CCI portal and in addition visualised in maps@awi contributing to the Permafrost Information System hosted by AWI.
The validation datasets for ground temperature will be published as standardised depth-time series in form of a permafrost community data publication on PANGAEA in the course of 2023, the validation dataset for active layer depths will be published accordingly at a later step.
.

3.4 Data documentation

The data documentation is available on the ESA CCI webpage (https://climate.esa.int/en/projects/permafrost/key-documents/).

4 PRODUCT FORMATS

4.1 Product projection system

The Coordinate Reference System (CRS) used for the global permafrost products in year 1 will be Polar Stereographic projections (Arctic and Antarctic) based on the World Geodetic System 84 (WGS84) reference ellipsoid. The coordinates are specified in meters. In year 2 of phase 2, the projection will be changed to the specifications of the lst_cci datasets, as they will be used as input. Information on product projection, ellipsoid and pixel size will be included in the NetCDF.

4.2 Subsets

Generation of subsets for America and Eurasia will be considered for year 2.

4.3 File formats

All datasets are provided in NetCDF format.

4.4 Product file naming conventions

The files for each product type are named as follows:

ESACCI-<CCI Project>-<Processing Level>-<Data Type>-<Product String>[-<Additional Segregator>]-<Start Date>-<End Date>-fv<File version>.nc

<CCI Project>
PERMAFROST for permafrost_cci

<Processing Level>
L4 for Level 4; Data sets are created from the analysis of lower level data, resulting in gridded, gap-free products.

<Data Type>
GTD, when the parameter is ground temperature at a certain depth, ALT, if the parameter is active layer thickness, PFR if the parameter is permafrost extent (fraction), PFF if the parameter is permafrost-free fraction, PFT if the parameter is fraction underlain by talik and PZO if the parameter is permafrost zone.

<Product String> : <source>_<algorithm>
MODIS_ CRYOGRID or ERA5_MODISLST_BIASCORRECTED
<Source>

- MODIS - MODIS Landsurface temperature is used as the main input for the L4 production for 2003-2018 data. Sensors of auxiliary data are listed in the meta data.
- ERA5 - Downscaled and bias corrected ERA reanalyses data based on statistics of the overlap period between ERA reanalysis and MODIS LST are used for data before 2003. Sensors of auxiliary data are listed in the meta data.

<algorithm>

- CRYOGRID – data from CRYOGRID algorithm
- MODISLST_BIASCORRECTED - Downscaled and bias corrected ERA reanalyses data based on statistics of the overlap period between ERA reanalysis and MODIS LST are used for data before 2003. Sensors of auxiliary data are listed in the meta data

<Additional Segregator>
This should be AREA<TILE_NUMBER>_<Layer type>
<TILE_NUMBER>being the tile number the subset index: 1- global, 2-North America, 3-Eurasia, 4-Northern Hemisphere
<Layer type>

- PP: layer type 1, corresponding to value of the permafrost parameter.

<Start Date> and <End Date>
The identifying date for this data set:
Format is YYYYMMDD, where YYYY is the four digit year, MM is the two digit month from 01 to 12 and DD is the two digit day of the month from 01 to 31.

fv<File Version>
File version number in the form n{1,}[.n{1,}] (That is 1 or more digits followed by optional . and another 1 or more digits). The most recent version is fv02.0 (released in May 2020).

Examples:
ESACCI-PERMAFROST-L4-GTD-MODIS_CRYOGRID-AREA4_PP-2011-fv02.0.nc
ESACCI-PERMAFROST-L4-GTD-ERA5_MODISLST_BIASCORRECTED-AREA4_PP-1997-fv02.0.nc

4.5 File meta data - NetCDF

The following attributes are included in the NetCDF file:

Global Attribute	Content
title	ESA CCI permafrost <parameter name>
institution	University of Oslo
source	<text>
history	YYYY-MM-DD HH:MM:SS
references	http://cci.esa.int/Permafrost [and publications]
tracking_id	<xxxxxxxx-yyyy-zzzz-nnnn-mmmmmmmmmmmm> a UUID (Universal Unique Identifier) value
Conventions	CF-1.9
product_version	<number>

Global Attribute	Content
summary	<text>
keywords	<text>
id	<filename>
naming authority	no.uio
keywords_vocabulary	NASA Global Change Master Directory (GCMD) Science Keywords
cdm_data_type	Grid
comment	These data were produced at ESACCI as part of the ESA Permafrost CCI+ project Contract No 4000123681/18/I-NB
date_created	<file creation date>
creator_name	University of Oslo
creator_url	https://www.uio.no/english/
project	Climate Change Initiative - European Space Agency
geospatial_lat_min	30
geospatial_lat_max	90
geospatial_lon_min	-180
geospatial_lon_max	180
geospatial_vertical_min	0.0
geospatial_vertical_max	0.0
time_coverage_start	YYYYMMDDTHHMMSSZ
time_coverage_end	YYYYMMDDTHHMMSSZ
time_coverage_duration	P<number of years>Y
time_coverage_resolution	P<number><unit>
standard_name_vocabulary	CF Standard Name Table v73
license	ESA CCI Data Policy: free and open access
platform	<name>
spatial_resolution	<number><
geospatial_lat_units	none
geospatial_lon_units	none
geospatial_lon_resolution	<number><
geospatial_lat_resolution	<number><
key_variables	<name>

Global Attribute	Content
Format_version	CCI Data Standards v2.2

5 REFERENCES

5.1 Bibliography

Anderson D.M. and Morgenstern N.R., 1973: Physics, chemistry and mechanics of frozen ground: A review Proceedings Second International Conference on Permafrost, Yakutsk, U.S.S.R., July 1973, North American Contribution, U.S. National Academy of Sciences, Washington, D.C., pp. 257-288

Brown R.J.E., 1967: Permafrost Map of Canada. National Research Council Canada, Pub. NRC 9769 and Geological Survey of Canada, Map 1246A (with marginal notes)

Brown R.J.E., 1970: Permafrost in Canada: Its influence on northern development. University of Toronto Press, Toronto 234 p.

Brown R.J.E., 1971: Characteristics of the active layer in the permafrost region of Canada. Proceedings Seminar on Permafrost Active Layer, May 1971, National Research Council Canada, Associate Committee on Geotechnical Research.

Brown R.J.E., 1978: Permafrost Map of Canada. In: Hydrological Atlas of Canada, Department of Fisheries and Environment, Ottawa, Canada, Plate No. 32.

Brown et al. 1997: Circum-Arctic Map of Permafrost and Ground Ice Conditions, International Permafrost Association; United States Geological Survey

Carlson H. and Kersten M.S., 1953: Calculation of depts of freezing and thawing under pavements. U.S. National Research Council, Highway Research Board, Bulletin No. 71, pp.81-98 (includes Discussion by H.P. Aldrich and H.M. Paynter).

Heginbottom, J.A., 1984: The mapping of permafrost. Canadian Geographer, Vol. 28, No.1, pp. 78-83.

Heginbottom, J.A., Radburn, L.K., 1992: Permafrost and Ground Ice Conditions of Northwestern Canada (Mackenzie Region). National Snow and Ice Data Center, Boulder, CO, USA.

Johnston, G.H. (Editor), 1981: Permafrost: Engineering Design and Construction. John Wiley & Sons, Canada Ltd., Totonto, 540p.

Kudryavtesv V.A., (Editor) 1978: Obshcheye merzlotovedeniya (Geokriologiya) (General permafrost science) In Russian. Izd. 2, (Edu 2) Moskva (Moscow), Izdatel'stvo Moskovskogo Universiteta, (Moscow University Editions), 404 p

Lunardini V.J., 1978: Theory of n-factors and correlation of data. Prodeedings Third International Conference of Permafrost, Edmonton, Alberta, July 1978, National Research Council Canada, Ottawa, Vol. 1, pp 41-46.

Lunardini V.J., 1981: Heat Transfer in Cold Climates. Van Nostrand Reinhold, New York, N.Y. 704p.

Mackay J.R., 1972a: Offshore permafrost and ground ice, southern Beaufort Sea, Canada. Canadian Journal of Earth System Sciences, Vol. 9, No. 11, pp. 1550-1561.

Mackay J.R., 1972b: The world of underground ice. Annals Association American Geographers, Vol. 62, No.1, pp 1-22.

Muller S.W, 1943: Permafrost or permanently frozen ground and related engineering problems. U.S. Engineers Office, Strategic Engineering Study, Special Report No. 62. 136p. (Reprinted in 1947, J. W. Edwards, Ann Arbor, Michigan, 231p.)

Obu, Jaroslav; Westermann, Sebastian; Kääb, Andreas; Bartsch, Annett (2018): Ground Temperature Map, 2000-2016, Northern Hemisphere Permafrost. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, https://doi.org/10.1594/PANGAEA.888600

Obu J., S. Westermann, A. Bartsch, N. Berdnikov, H. H. Christiansen, A. Dashtseren, R. Delaloye, B. Elberling, B. Etzelmüller, A. Kholodov, A. Khomutov, A. Kääb, M. O. Leibman, A. G. Lewkowicz, S. K. Panda, V. Romanovsky, R. G. Way, A. Westergaard-Nielsen, T. Wu, J. Yamkhin, D. Zou (2019): Northern Hemisphere permafrost map based on TTOP modelling for 2000-2016 at 1 km2 scale. Earth-Science Reviews, 193, 299-316.

Penner E., 1970: Thermal conductivity of frozen soils. Canadian Journal of Earth Sciences, Vol. 7, No. 3, pp. 982-987

Péwé T.L., 1983: Alpine permafrost in the contiguous United States: A review, Arctic and Alpine Research, Vol. 15, No.2, pp. 145-156

Pollard W.H. and French H.M., 1980: A first approximation of the volume of ground ice, Richards Island, Pleistocene Mackenzie Delta, Northwest Territories, Canada. Canadian Geotechnical Journal, Vol. 17, No. 4, pp. 509-516.

van Everdingen, R.O., 1976: Geocryological terminology, Canadian Journal of Earth Sciences, Vol. 13, No. 6, pp.862-867

van Everdingen R.O., 1985: Unfrozen permafrost and other taliks. Workshop on Permafrost Geophysics, Golden, Colorado, October 1984 (J. Brown, M.C. Metz, P. Hoekstra, Editors). U.S. Army, C.R.R.E.L., Hanover, New Hampshire, Special Report 85-5, pp.101-105

Washburn, A.L., 1973: Periglacial processes and environments. Edward Arnold, London, 320p.

Washburn, A. L., 1979: Geocryology. Edward Arnold, London, 406p.

Westermann, S., Ingeman-Nielsen, T., Scheer, J., Aalstad, K., Aga, J., Chaudhary, N., Etzelmüller, B., Filhol, S., Kääb, A., Renette, C., Schmidt, L. S., Schuler, T. V., Zweigel, R. B., Martin, L., Morard, S., Ben-Asher, M., Angelopoulos, M., Boike, J., Groenke, B., Miesner, F., Nitzbon, J., Overduin, P., Stuenzi, S. M., and Langer, M.: The CryoGrid community model (version 1.0) – a multi-physics toolbox for climate-driven simulations in the terrestrial cryosphere, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2022-127, in review, 2022.

Williams, J.R., 1965: Ground water in permafrost regions: An annotated bibliography. U.S. Geological Survey, Professional Paper 696, 83p.

5.2 Acronyms

AD	Applicable Document
ALT	Active Layer Thickness
AWI	Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research
B.GEOS	b.geos GmbH
CCI	Climate Change Initiative
CRG	Climate Research Group
CRS	Coordinate Reference System
DARD	Data Access Requirements Document
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
GCMD	Global Change Master Directory
GIPL	Geophysical Institute Permafrost Laboratory
GTD	Ground Temperature at certain depth
GTN-P	Global Terrestrial Network for Permafrost
GUIO	Department of Geosciences University of Oslo
IPA	International Permafrost Association
IPCC	Intergovernmental Panel on Climate Change
LST	Land Surface Temperature
MAGT	Mean Annual Ground Temperature
MAGST	Mean Annual Ground Surface Temperature
NetCDF	Network Common Data Format
NSIDC	National Snow and Ice Data Center
PFR	Permafrost extent (Fraction)
PFF	Permafrost-Free Fraction
PFT	Permafrost underlain by Talik
PSD	Product Specifications Document
PSTG	Polar Space Task Group
PZO	Permafrost Zone

RD	Reference Document
RMSE	Root Mean Square Error
RS	Remote Sensing
SLF	Institut für Schnee- und Lawinenforschung, Davos
SU	Department of Physical Geography Stockholm University
TSP	Thermal State of Permafrost
UAF	University of Alaska, Fairbanks
UNIFR	Department of Geosciences University of Fribourg
URD	Users Requirement Document
WGS 84	World Geodetic System 1984
WUT	West University of Timisoara