permafrost
cci

CCI+ PHASE 2 – NEW ECVS

PERMAFROST

D2.4 ALGORITHM DEVELOPMENT PLAN (ADP)

VERSION 5.0

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4.0	10.05.2023	Integration plans into the CryoGRID community model added	SW, AB
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EXECUTIVE SUMMARY

The ESA Permafrost_cci project for the first time demonstrates transient permafrost modelling covering the entire Northern Hemisphere at 1km scale, largely forced by Earth Observation data sets. While such algorithms have been demonstrated in a variety of studies before, the effort in Permafrost_cci is significantly larger from a computational point of view, making the setup of an automatic processing chain on a supercomputing cluster a major challenge which has been completed successfully in years 1 and 2 of the Permafrost_cci project. Subtasks included the integration of existing processing chains, in particular the preprocessing of land surface temperature records from the ESA GlobPermafrost project, as well as the compilation of the CryoGrid CCI ground thermal model, which is a computationally efficient version of existing model schemes. Also, for the first time, an ensemble representation of subpixel spatial variability of Permafrost ECV variables has been implemented in a processing chain with a transient representation of the ground thermal regime. Furthermore, the processing chain is implemented in a scalable fashion on a high-performance computing cluster, so that extended computation capacities in the future can be fully exploited, e.g. by increasing the density of the ensemble representation for individual pixels.

In CCN4, the Permafrost_cci processing chain has been implemented in the modular setup of the CryoGrid community model which makes it possible to develop the algorithm further and efficiently implement additions and improvements. This not only makes the CryoGrid CCI model available to a wider user community, but also offers the possibility to use parts of the processing chain together with other models (e.g. process-rich and computationally more expensive models). Together with the users of the CryoGrid community model, we will assess the possibility to train machine learning-based emulators on the CryoGrid model results which has the potential to significantly speed up processing, so that available computing resources can for example be used to compute more ensemble members and thus improve the precision and accuracy of the permafrost extent product. Finally, in CCN4 we will test a data assimilation procedure for snow extent from Snow_CCI which could be employed in tundra regions to constrain the melt-out data and potentially also the pre-melt snow water equivalent which has the potential to improve the overall snow depths and thus modelled ground temperatures in winter.

1 INTRODUCTION

1.1 Purpose of the document

This document provides an overview over the planned development of the Permafrost_cci algorithm within the project years. The document outlines both planned changes of the ground thermal model CryoGrid CCI and incorporation of new input data sets, which are largely derived from other CCI projects.

1.2 Structure of the document

This document summarizes the main characteristics of the algorithm selected for Permafrost_cci in Section 2. Section 3 provides an overview over existing processing chains, while Section 4 details planned algorithm improvements in the course of the project.

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.

1.4 Reference Documents

[RD-1] Bartsch, A., Matthes, H., Westermann, S., Heim, B., Pellet, C., Onacu, A., Strozzi, T.(2024): ESA CCI+ Permafrost User Requirements Document, v4.0

[RD-2] Bartsch, A., Westermann, Strozzi, T., Wiesmann, A., Kroisleitner, C. (2023): ESA CCI+ Permafrost Product Specifications Document, v4.0

[RD-3] Bartsch, A., Westermann, S., Heim, B., Wieczorek, M., Pellet, C., Barboux, C., Kroisleitner, C., Strozzi, T. (2020): ESA CCI+ Permafrost Data Access Requirements Document, v2.0

[RD-4] 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-5] 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-6] Westermann, S., Bartsch, A., Strozzi, T. (2024): ESA CCI+ Product Validation and Assessment Report, v5.0

[RD-7] Heim, B., Wieczorek, M., Pellet, C., Delaloye, R., Bartsch, A., Strozzi, T. (2024): ESA CCI+ Product Validation and Intercomparison Report, v4.0

1.5 Bibliography

A complete bibliographic list that support 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 term relevant for the parameters addressed in CCI+ Permafrost. A comprehensive glossary is available as part of the Product Specifications Document [RD-2].

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.

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.

2 JUSTIFICATION ON THE ALGORITHM CHOSEN

In Permafrost_cci, we retrieve the parameters ground temperature and active layer thickness in a transient fashion, which are the parameters that define the Essential Climate Variable permafrost. As a result of general considerations, a review of published methods for ECV generation, and model intercomparison with other existing permafrost simulation tools, transient ground thermal modeling forced by remote sensing data sets has been identified as the most suitable algorithm. The Permafrost_cci processing chain has been implemented based on these considerations, the, comprising the new CryoGrid CCI ground thermal model implemented in the CryoGrid community model (Westermann et al., 2023).

As basis for the benchmarking in Permafrost_cci, ground temperature from borehole data available through GTN-P and active layer thickness through CALM have been used, assessing algorithm performance primarily through measures such as correlation, root mean square error and standard deviation [RD-7]. The algorithm selected in Permafrost_cci is able to achieve threshold requirements in many categories, while future algorithm development is expected to lead to a further improved performance.

3 EXISTING PRODUCTION LINES

This section provides an overview over existing production lines for both input data sets for Permafrost_cci modelling and the actual model frameworks.

The ESA GlobPermafrost project has established production lines for gap-filling of remotely sensed land surface temperatures (LST) from MODIS, using ERA reanalysis data. These production lines are used as the basis for Permafrost_cci processing, but they have been modified to incorporate the new ERA-5 reanalysis instead of ERA-interim. In ESA GlobPermafrost, another production line for assessing the fractional cover of 300m from Landcover_cci within 1km grid cells has been established. This has been employed directly for Permafrost_cci. Furthermore, a production line for subpixel ensemble generation has been created in ESA GlobPermafrost, which forms the basis for ensemble generation in Permafrost_cci. To allow global ECV processing at the resolution of 1km requested by users [RD-1], the first phase of Permafrost_cci has implemented a production line centered around the CryoGrid CCI ground thermal model was implemented, with which ECV production is accomplished. This production line has been continuously improved during Permafrost_cci and in CCN4 has been fully implemented in the CryoGrid community model which offers significant potential for further model development in the future, together with an active user and developer community of more than 30 researchers mainly at European institutions.

4 ALGORITHM DEVELOPMENT PLANS

Here, we document the possibilities for further development of the Permafrost_cci algorithm, which is at present implemented on the Saga supercomputing cluster in Trondheim, Norway. Compared to published studies using similar ground thermal models (e.g. Jafarov et al., 2012), the computational effort ECV processing is considerably higher due to the global focus at the relatively high spatial resolution of 1km, so that model tuning is considerably more difficult than in most previous efforts. The plan must therefore be considered tentative and will be adapted further according to intermediate results achieved.

The Permafrost_cci algorithm facilitates production of the Permafrost ECV at 1km pixel size including a representation of subgrid variability with a model ensemble. Here, we provide detailed information on the different steps of the processing chain, as well as possible modifications.

- Download of all required raw input data sets and establishment of an input archive on the Norwegian NIRD (National e-Infrastructure for Research Data; documentation.sigma2.no/storage/nird.html) storage facility. The download of MODIS LST and all other data sets required for the processing chain has been completed. One major challenge is that the data sets on NIRD cannot directly be accessed from the Saga HPC cluster, which needs to be addressed in the future to improve the processing speed. However, this is contingent on hardware changes of the Sigma2 company responsible for HPC operations in Norway, so it is beyond the control of Permafrost_cci.
- Establishment of a preprocessing chain to compile eight-day averages of all CryoGrid CCI forcing data sets. This subtask is now implemented in a modular fashion, so that it is possible to switch between different input data sets without changing the other parts of the processing chain. To simplify this step further, the model grid has been adapted to a geographic coordinate system for all input data sets.
- Compilation of the CryoGrid CCI model for processing, including a spin-up procedure to estimate the initial state. The results of year 2 suggest a sufficient performance to meet most threshold requirements for the ECV product. Further improvements are the integration of a snow-melt representation based on a surface energy balance formulation targeted in CCI+ iteration 1.
- Postprocessing of model results to compile the Permafrost ECV variables, i.e. annual averages of ground temperature, maximum annual thaw depth (i.e. active layer thickness) and permafrost fraction. Further parameters requested by users have been added, e.g. annual maximum and minimum temperatures, as well as ground temperature products at specific points in time which allow assessing the seasonal temperature cycle.

In CCN4 iteration 1, we have delivered the first N Hemisphere product from 1997 to 2021 at 1km pixel size, with a model ensemble of seven members, which includes the epochs 1997/1998, 2007/08 and 2017/2018. In the course of this work, the main processing chain has been implemented and tested, with optimizations of both runtime and model performance continuously ongoing. Due to the significant runtime of 1-2 months for a Northern Hemisphere run (depending on overall compute load on the HPC cluster), as well as the available computational resources, it is challenging to accomplish several iterations within a year, so that algorithm development plans must be understood as tentative.

In CCN4, we will test the performance of a data assimilation procedure for Snow_cci snow extent data which can improve the representation of the snow melt-out date in the processing chain which is a critical event for the seasonal thawing of the active layer. A surface energy balance formulation for snow melt has already been implemented in CryoGrid CCI which makes it possible to use the snow melt-out date to constrain the pre-melt snow water equivalent and snow depth and thus potentially achieve a better representation of the ground thermal regime during winter. Furthermore, we have started a development to add machine-learning based emulators in the CryoGrid community model. The main idea is to use the results of physically-based permafrost models like CryoGrid CCI to train the emulator, which can then calculate the Permafrost ECV parameters (like active layer thickness, mean annual ground temperature) more efficiently than the physically-based model. While the potential gains in computation speed are still unclear, this procedure would in particular make it possible use the available computation resources to simulate a denser ensemble which would increase the precision and accuracy of the permafrost extent product.

Further modifications in the future could include:

- Excess ground ice and thermokarst development could be represented within the Permafrost_cci processing, using the method of laterally coupled tiles already implemented in the CryoGrid community model (Nitzbon et al., 2019; Westermann et al., 2023). Possible target landforms for such a scheme are in particular tundra polygons which are transformed form low-center polygons to high-center polygons upon thawing. To represent this thermokarst dynamics, a model scheme with three coupled tiles as in Nitzbon et al. (2019) could be implemented in CryoGrid CCI, using the process representation form the normal processing chain for each individual tile. In a similar way, degrading peat plateaus can be targeted, as demonstrated in CryoGrid by Martin et al. (2021).
- The ensemble generation could potentially be improved, especially taking correlations between different input factors explicitly into account. This is especially important for improvement of the model representation of carbon-rich permafrost peatlands where dry conditions are

associated with low snow depths on permafrost-bearing peat plateaus, while permafrost-free wet fen areas are associated with a high soil moisture and high snow depths (Quinton and Baltzer, 2013; Aas et al., 2019).

- Implementation of wintertime rain and melt events in the snow module can potentially lead to improved performance in maritime permafrost regions, such as on Svalbard (Putkonen and Roe, 2013; Westermann et al., 2011).
- Based on the Fire_cci products, information on forest fires could be implemented as a disturbance in the CryoGrid CCI model, including the burnt area and the timing of the fire. The effect of a fire would be represented by modifying ground stratigraphies (i.e. reducing the organic content near the surface), which leads to increased thaw depths in the CryoGrid CCI model, in qualitative agreement with observations from burn sites (e.g. Brown et al., 1983; Taş et al., 2014).

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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