CCI+ PHASE 1 – NEW ECVS

PERMAFROST

D2.4 ALGORITHM DEVELOPMENT PLAN (ADP)

VERSION 1.0

28 FEBRUARY 2019

PREPARED BY

Document Status Sheet

Issue	Date	Details	Authors
0.1	04.12.2018	Initial version	T. Strozzi (GAMMA)
0.2	22.2.2018	Draft	SW
0.3	25.02.2019	Draft update – first iteration	SW, AB
0.4	26.02.2019	Draft update – second iteration	SW, AB, BH
1.0	28.02.2019	Final version	AB

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EXECUTIVE SUMMARY

The ESA Permafrost_cci project for the first time aims for global application of a transient ground thermal model at 1km scale, largely forced by Earth Observation data sets. While such algorithms have been demonstrated in a variety of studies before, the effort planned in Permafrost_cci is significantly larger from a computational point of view, making the setup of an automatic processing chain on a supercomputing cluster the major task in the year 1 of the project. Subtasks include the integration of existing processing chains from previous projects, in particular the preprocessing of land surface temperature records form 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 will be implemented in the processing chain. A major emphasis is put on parallel implementation and scalability of the entire algorithm, which is a prerequisite to exploit the extended computation capacities in the future, e.g. by increasing the density of the ensemble representation for individual pixels. Due to the significant processing time of several months even on a supercomputing cluster, it is not possible to achieve fast turnover cycles in model development, which is a major challenge for the Permafrost_cci project. The algorithm development plan for years 2 and 3 is therefore tentative, and efforts must be directed according to the performance of year 1 products. Major targeted improvements are the implementation of a state-of-the-art ground stratigraphy product based on a synthesis effort of several thousand soil profiles, as well as the extension of the model period back to 1979/1980, which will significantly improve the spin-up of the ground temperature profile and thus model results for the target epochs 1997/98, 2007/2008 and 2017/2018. Furthermore, novel data sets from other CCI projects will be incorporated, which will not only improve the performance of the Permafrost_cci algorithm, but also increase consistency within the CCI family of data sets. Finally, significant model development will be dedicated towards improving the validation procedure by taking the scale difference between near-point field observations and the 1km pixels of the Permafrost ECV products explicitly into account.

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 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., Kroisleitner, C., Strozzi, T.(2019): ESA CCI+ Permafrost User Requirements Document, v1.0

[RD-2] Bartsch, A., Westermann, Strozzi, T., Wiesmann, A., Kroisleitner, C. (2019): ESA CCI+ Permafrost Product Specifications Document, v1.0

[RD-3] 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-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. (2019): ESA CCI+ Product Validation and Assessment Report, v1.0

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 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 JUSTIFICATION ON THE ALGORITHM CHOSEN

In Permafrost_cci, we aim to 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. At the same time, successful production of global permafrost extent and ground temperature products (static in time) with the same input data sets in the GlobPermafrost project suggests that transient application is indeed possible. Based on these considerations, the Permafrost_cci processing chain has been implemented, compiling the CryoGrid CCI ground thermal model based on the well-established CryoGrid 2 simulation tool (Westermann et al., 2013; 2017).

As basis for the benchmarking in Permafrost_cci, ground temperature from borehole data available through GTN-P and active layer thickness through CALM are used, assessing algorithm performance primarily through measures such as correlation, root mean square error and standard deviation. A preliminary benchmark of results of the Permafrost_cci processing chain shows a Root Mean Square Error (RMSE) of about 1.9K with respect to permafrost temperature, which must be confirmed when improved data sets for ground temperature (as compiled by the validation team in Permafrost_cci) are available. For the active layer thickness, the ground stratigraphy employed in the modelling is the decisive factor if a good match with field data can be achieved. In summary, the algorithm selected in Permafrost_cci can likely deliver threshold requirements in almost all categories, while likely achieving target requirements for important categories, such as the spatial resolution of the resulting products.

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 are modified to incorporate the new ERA-5 reanalysis instead of ERA-interim. Also in ESA GlobPermafrost, a production line for assessing the factional cover of 300m from Landcover_cci within 1km grid cells has been established. This can be employed directly for Permafrost_cci. Furthermore, a production line for subpixel ensemble generation has been created in ESA GlobPermafrost, which, however, is optimized for equilibrium permafrost models. Nevertheless, it can form the basis for ensemble generation in Permafrost_cci. The SatPerm project funded by the Research Council of Norway (2015-2018) has established a production line for the ground thermal model CryoGrid 2, as employed by Westermann et al. (2015). With this model, Permafrost ECV generation is possible but the algorithm implementation is not computationally efficient enough to allow global ECV processing at 1km pixel size. Since this resolution was requested by users [RD-1], the production line needs to be strongly modified which resulted in the compilation of the CryoGrid CCI ground thermal model applicable for Permafrost_cci.

4 ALGORITHM DEVELOPMENTS PLAN

Here, we document the plan for further development of the Permafrost_cci algorithm, which concerns especially years 2 and 3 of the project. We emphasize that a similar algorithm has never before been demonstrated at such relatively fine spatial scale. Compared to published studies using similar ground thermal models (e.g. Jafarov et al., 2012), the computational effort is considerably increased, and the global focus makes model tuning a lot more difficult than in most previous efforts. The plan must therefore be considered tentative and will be adapted according to intermediate results achieved in years 1 and 2.

In year 1, the main goal is to implement the Permafrost_cci algorithm so that the Permafrost ECV can be obtained at 1km pixel size including a representation of subgrid variability with a model ensemble. This work is structured as follows:

- 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.
- Compilation of a workload distribution system, which splits the processing in parallel jobs that can run optimally on the cores of the Abel Supercomputing cluster (www.uio.no/english/services/it/research/hpc/abel/). The workload distribution system takes both the sequential runtime on each core and the required memory per core into account. It includes both the preprocessing and the actual CryoGrid CCI simulations.
- Establishment of a preprocessing chain to compile eight day averages of all CryoGrid CCI forcing data sets.
- Setup of the CryoGrid CCI model on the Abel Supercomputing cluster, including a spin-up procedure to estimate the initial state. For global applications, the model must be amended with additional parametrizations for the snow module, e.g. to reproduce spatial patterns of snow densities (Vionnet et al., 2012).
- 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.

In year 1, we aim to deliver the first N Hemisphere product including major permafrost regions for epochs 2007/08 and 2017 at 1km pixel size, with a model ensemble of five members. At the end of year 1, the main processing chain will be implemented and tested, but will most likely not yet been fully optimized. The reason for this is the significant runtime of more than 2 months on order to achieve runs for the entire Northern Hemisphere, so that it is not possible to loop over several iterations in year 1. In years 2 and 3, the processing chain will be gradually optimized, building on the results of year 1. The algorithm development plan in years 2 and 3 must therefore be understood as tentative.

In year 2, we plan to integrate improved ground stratigraphies and combine the ESA CCI Landcover classification employed in year 1 with permafrost-focussed spatial classifications, e.g. existing maps of Yedoma extent as well as in-situ observations of ground stratigraphies (Hugelius et al., 2013). Furthermore, we will integrate land surface temperature and snow cover data sets from other CCI projects, if these are available in time for Permafrost ECV production in year 2. Furthermore, we will extend the model period to 1979-2018, with 1979-1995 used as spin-up period. Since remote sensing data for land surface temperature are not available for this initial period, we will compile a synthesized time series by correlating the Permafrost_cci forcing time with original ERA-5 data for the overlap period (e.g. 2003-2018). Extending the forcing time series will strongly improve the transient performance of the model, which is especially important for ground temperatures in deeper ground layers (more than 5m depth). If sufficient computation resources can be made available, the ensemble size will be increased further to ten ensemble members. In addition, the snow model implemented in CryoGrid CCI will be improved by including a snow melt model based on the surface energy balance, which is computed from ERA-5 data using the published scheme of Fiddes and Gruber (2014). For the validation procedure, we target a major improvement by using individual ensemble members for comparison to ground truth data from boreholes instead of ensemble averages. We expect that this will strongly moderate the scaling problem between the near-point-scale of borehole measurements and the 1m pixel size of the permafrost ECV products. For this purpose, it is necessary to establish a procedure that can estimate the best-fitting ensemble member for each borehole.

In year 3, we mainly plan to consolidate the measures taken in year 2. This in particular concerns the snow model in CryoGrid CCI. If possible, the ensemble size will be increased further to increase the precision of the permafrost extent product. Furthermore, we aim to refine the ensemble generation, 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). In maritime permafrost regions, implementation of wintertime rain events in the snow module can likely lead to improved performance (Putkonen and Roe, 2013;

Westermann et al., 2011). Finally, we will implement information on forest fires based on Fire_cci products. The idea is to modify 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).

5 REFERENCES

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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