CCI+ PHASE 2 – NEW ECVS

PERMAFROST

D2.3 END-TO-END ECV UNCERTAINTY BUDGET (E3UB)

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EXECUTIVE SUMMARY

This document provides an assessment of the end-to-end uncertainty budget that the Permafrost ECV products produced within the Permafrost_cci are associated with. These products are level 4, so they are based on a range of input data sets whose uncertainties propagate to the permafrost ECV products. These input products are remotely sensed land surface temperature, land cover classifications from ESA Landcover_cci, as well as various near-surface and pressure level fields from the ERA-5 reanalysis. The core of the processing chain is the ground thermal model CryoGrid CCI, which numerically solves the differential equation of heat conduction for a one-dimensional ground domain. The model has a highly nonlinear signal processing characteristic for the input data sets, including a strong dependence on the absolute values of modeled ground temperatures. In principle, computationally expensive ensemble methods could be employed in order to retrieve the uncertainty characteristics of the Permafrost ECV products based on the uncertainty characteristics of input data sets. However, due to the prohibitive computational cost, such methods cannot be applied on the global scale of the Permafrost_cci processing. Moreover, validation studies have shown that uncertainty estimates for input data sets such as remotely sensed land surface temperatures are not representative for arctic conditions, thus making them unsuitable for determining the resulting uncertainty of the Permafrost_cci products. Therefore, it is important to assess uncertainties by comparing to in-situ observations of permafrost parameters. Since these in-situ observations generally represent point or near-point observation, this spread of this model ensemble represents a first-order characterization of the expected uncertainty when comparing to in-situ measurements. Comparison of Permafrost_cci annual average temperatures to in-situ measurements in boreholes suggests that the ensemble spread slightly underestimates the true uncertainty of the Permafrost_cci ground temperature data, but it still is in the correct order of magnitude.

The uncertainties of land surface temperature are generally not well constrained especially in the poorly accessible permafrost regions, where validation data for e.g. surface temperatures are even more sparse than for permafrost temperatures and active layer thickness. Evaluation of uncertainty retrieval will evolve through throughout the project. We outline that it is imperative to base the end-to-end uncertainty budget to a large degree on comparison to direct field observations of the permafrost ECV variables.

1 INTRODUCTION

1.1 Purpose of the document

This document provides an overview of the main sources of uncertainty for the Permafrost ECV variables. As ECV generation relies on a ground thermal model (CryoGrid CCI), both the uncertainties of in the input data sets and of the model itself must be considered. Furthermore, as the model has a highly non-linear characteristics, error propagation of input uncertainties must be accounted for. In a strict sense, the nature of the input data sets (discrete classes vs. continuous variables) and the associated error characteristics (random error/ bias, error distribution), including potential correlations between errors of different input variables must be considered. Finally, uncertainties related to the spatial scales of data sets and the natural heterogeneity of permafrost landscapes must be taken into account.

1.2 Structure of the document

This document contains an assessment of the uncertainty propagation from the input data sets to the final Permafrost ECV products, taking the characteristics of the employed ground thermal model into account. Furthermore, the limitations of the algorithm with respect to neglected processes are assessed.

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. (2023): ESA CCI+ Permafrost User Requirements Document, v3.0

[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. (2023): ESA CCI+ Product Validation and Assessment 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 SOURCES OF ERRORS AND UNCERTAINTIES

2.1 Input data sets influencing product uncertainty

Surface temperature: For remotely sensed land surface temperatures (LST), three kinds of uncertainties occur which must be considered for permafrost ECV generation: i) the uncertainty of an individual measurement which is typically evaluated in validation studies (e.g. 1K for MODIS LST; Wan et al., 2004); ii) the uncertainty/bias of longer-term average surface temperatures computed from individual measurements; iii) the uncertainty due to the spatial variability of the true surface temperature at scales smaller than the sensor footprint (1km or larger). For computation of ground temperatures, only longer-term averages of surface temperatures are relevant, so that uncertainty (i) (which is the most widely reported for LST products) does not need to be considered, if one assumes it to be a random term (which averages out for longer periods). However, several studies have shown that the error of long-term averages computed from individual LST measurements can be significantly larger than the error of individual measurements (i.e. uncertainty (i)) in the Arctic, which is partly due to undetected clouds and partly due to neglecting cloudy periods without remotely sensed LST measurements (Langer et al., 2010; Soliman et al., 2012; Westermann et al., 2011a; 2012). With a long-term bias of up to 3 K (Westermann et al., 2012; 2017), this uncertainty is large enough to make permafrost ECV generation from remotely sensed land surface temperatures impossible. Moreover, the bias is directional especially in winter conditions, leading to a systematic underestimation of seasonal average LST (Westermann et al., 2012). To moderate these difficulties, gap-filling as demonstrated in Westermann et al. (2017) is employed in Permafrost_cci. This way, a meaningful assessment of the permafrost ECV variables becomes possible (Fig. 1) Westermann et al., 2015; 2017). The spatial variability of true surface temperatures (uncertainty iii) can be immense even over short distances of tens of meters, but the variability of longer-term (e.g. eight day) averages becomes significantly smaller (Langer et al., 2010; Westermann et al., 2011a), so that it is indeed appropriate to employ remotely sensed LST at 1km spatial resolution for permafrost ECV generation. Permafrost_cci ECV generation relies on MODIS LST which is affected by the error sources described above, making it unfeasible to use provided uncertainty estimates in a meaningful way.

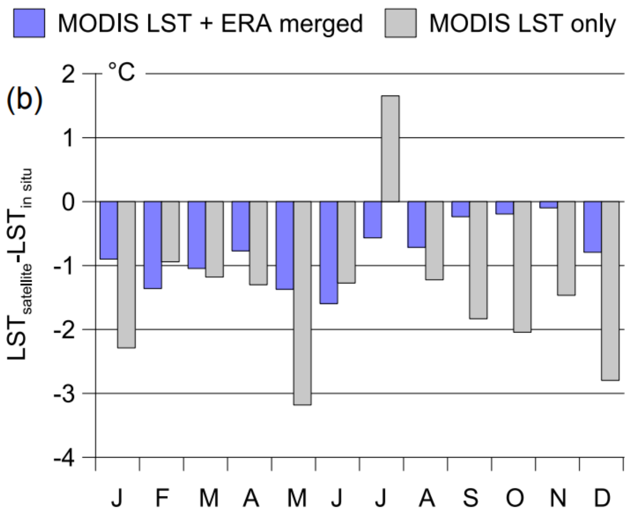

Figure 1: Effect of gapfilling remotely sensed MODIS LST data with ERA reanalysis near-surface fields of air temperatures for the Samoylov Island permafrost observatory, one of the few sites in the Arctic. The figure is taken from Westermann et al. (2017).

Ground properties – classification: To determine the ground stratigraphy, Permafrost_cci relies on remotely sensed landcover products. Three major sources of uncertainty can be distinguished: i) the thematic content of the classes, which can compromise their usability for permafrost ECV generation; ii) erroneous classifications of pixels; and iii) insufficient spatial resolution to capture the true spatial variability of the landcover (judged according to the thematic content of the distinguished classes).

Fig.2 showcases problems i) and ii) for an area in Western Siberia, where both peatlands and river floodplains are classified as wetlands in the landcover_cci classification. In the stratigraphy, however, these areas are expected to show major differences, due to different mechanisms of soil formation. Further issues include the assignment of the class bare ground across most tundra area which feature shrubs and significant moss coverage (Bartsch et al. 2016).

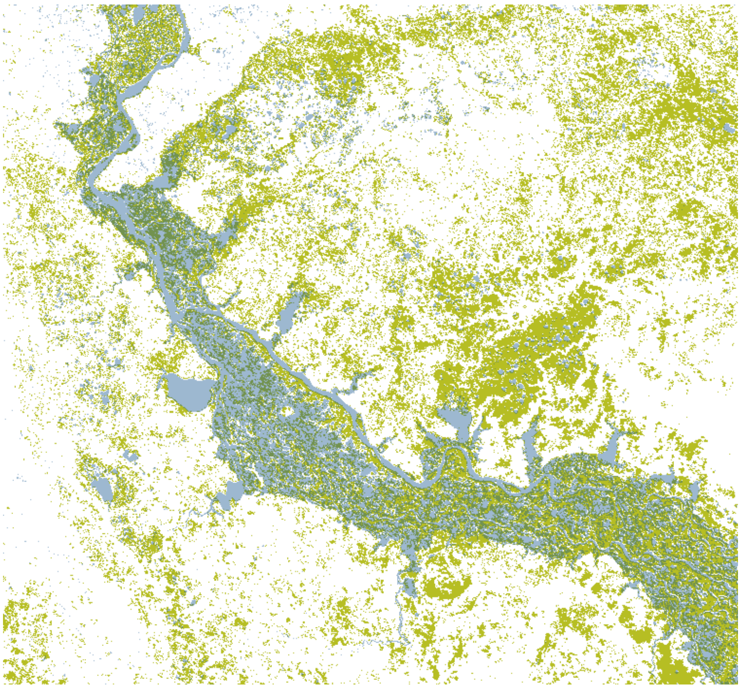

Figure 2: Example of classification ambiguity in the Upper Ob-river area (polar stereographic projection): Bright green – wetlands in CCI Landcover, blue – maximum water extent in 2007 ESA STSE ALANIS Methane project (Reschke et al. 2012), dark green overlap of both sources

The spatial resolution of the ESA CCI landcover product is 300m, which facilitates resolving most landcover boundaries relevant for permafrost ECV generation (target resolution 1km), so that this source of uncertainty can in most cases be considered negligible. However, small, isolated permafrost features surrounded by permafrost ground, e.g. palsas, could in some cases not be resolved to the limited resolution. It has been also shown that spatial resolution determines the ability to capture relevant landcover classes in tundra environments (Virtanen and Ek 2014).

Ground properties – stratigraphies: The stratigraphies applied for the different classes are oriented at field measurements, which are derived from a significant number of soil pedons (i.e. vertical sections allowing the describe ground properties from drill cores or natural exposures), representing the same data base as for the widely accepted assessment of permafrost carbon (Hugelius et al., 2013). Therefore, mean values and standard deviations are available, which makes an explicit assessment of uncertainty possible. The main challenge is that the representativeness of the set of samples is difficult to assess. Furthermore, the uncertainty of the stratigraphy is closely linked to uncertainty i) in "*Ground properties – classification*" in the previous section. Essentially, a large standard deviation of values within a class might indicate that the thematic classes are not selected in an adequate way. On the other hand, it could also indicate that ground stratigraphies feature a strong (natural) spatial variability within model pixels. We therefore employ the spread of the ground stratigraphies within landcover classes to generate the model ensemble in the Permafrost_cci processing chain, so that it explicitly contributes to the spread of the model ensemble.

2.2 Impact of the algorithm for uncertainty characterisation

We refer to the detailed study of Langer et al. (2013) who evaluated the uncertainty characteristics of a ground thermal model similar to the one used in Permafrost_cci with ensemble methods. While the results were obtained only for a single point in Northeast Siberia, more universal conclusions can be drawn in many cases. The main findings of this study can be summarized as follows:

a) average annual ground temperatures are most strongly influenced by the applied snow forcing, while surface temperatures and the ground stratigraphy have a smaller impact (considering realistic uncertainty ranges for these data sets).

b) active layer thickness, on the other hand, is mostly influenced by the applied ground stratigraphy, while land surface temperature and snow forcing have a much lower influence.

We consider these findings to be universally applicable for cold permafrost regions. In agreement with previous studies, active layer thickness is expected to be the most challenging variable, with the performance in most regions strongly dependent on the availability of a good ground stratigraphy product. For warm permafrost near the thaw threshold, however, sensitivities are likely different from the ones reported by Langer et al. (2013), and active layer thickness is influenced by surface temperatures and snow forcing more strongly.

A major challenge of the uncertainty assessment is that the uncertainty characteristic does not only depend on the absolute magnitude of the input data, but also on the history of the system, i.e. the entire record of forcing data applied previously. As an example, ground temperatures at a certain depth are initially influenced by the applied surface temperatures cold permafrost conditions, as stated previously. When the permafrost warms and finally crosses the thaw threshold, ground temperatures are confined to near 0 °C for a prolonged period (depending on the ground ice content, often many years), and the sensitivity to the applied forcing vanished almost completely. When near-surface permafrost has finally disappeared, the sensitivity towards the forcing increases again, but likely with a different uncertainty characteristic than in the initial state. Due to the non-linear nature of this behavior, ensemble methods as described in Langer et al. (2013) are the preferred way to assess the uncertainty characteristics. However, this requires the uncertainty characteristics of the input data to be fully known, which is mostly not the case.

Finally, there are several processes unaccounted for the Permafrost_cci scheme, which cause additional uncertainty that is inherently difficult to quantify. Examples are:

- Melting of excess ground ice, which causes active layer thickness to be stable in the course of warming instead of increasing (e.g. Streletskiy et al., 2017), as a ground thermal model like CryoGrid CCI would predict.
- Lateral fluxes of heat and water over lateral distances much shorter than the pixel size of the Permafrost CCI products can affect the ground thermal regime (Aas et al., 2019).
- Infiltration of rainwater can lead to advection of heat which is not considered in CryoGrid CCI.
- Fires are known to modify the organic content within the active layer, which causes active layer to deepen drastically and even permafrost to disappear (e.g. Burn, 1998).
- Wintertime rain events can lead to strong warming of permafrost (e.g. Westermann et al., 2011b), but this process is not represented in the model scheme.

While these points could in principle be accounted for in models, application at global scale is in most cases not possible in Permafrost_cci, partly due to prohibitive increases in computational effort, but mainly due to the lack of suitable input data sets on global scale. The additional uncertainty inflicted by missing processes is therefore difficult to quantify. Some of the missing processes (e.g. wintertime rain events), however, could be implemented in non-operational, exploratory versions of CryoGrid CCI which would facilitate assessing the additional uncertainty of Permafrost ECV products. However, this would in most cases require in-depth studies at specific sites or regions which is beyond the focus of Permafrost_cci.

2.3 Uncertainty of validation data

The World Meteorological Organization (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 Permafrost Monitoring (TSP) and the Circumpolar Active Layer Monitoring program (CALM) (Brown et al., 2000), including standards for measurements and data collection (Clow 2014). These comprehensive datasets include variable timeframes from hourly over annually to sporadic ground temperature and active layer depth measurements covering a wide range of different vegetation and permafrost types.

In addition to the main source for validation with GTN-P data collection of ground temperature measurements in TSP and active layer depth in CALM further suitable records will come from national and regional monitoring networks of ground temperature such as ROSHYDROMET in Russia and PERMOS in Switzerland.

For Permafrost ECV Ground Temperature we provide conservative estimates on

ground temperature accuracy – estimated impact on ground temperature 0.1K. [Biskaborn et al. 2019 provide a summary on estimated ground temperature accuracy. Ground Temperature in soil profiles or boreholes is measured either by lowering a calibrated thermistor into a borehole, or recorded using permanently installed multi-sensor cables Measurements are recorded either manually with a portable temperature system or by automated continuous data logging. The reported measurement accuracy of the temperature observations, including manual and automated logging systems, varied from ±0.01 to ±0.25 °C with a mean of ±0.08 °C. Previous tests have shown the comparability of different measurement techniques to have an overall accuracy of ±0.1 °C. Thermistors are the most commonly used sensors for borehole measurements. Their accuracy depends on (1) the materials and process used to construct the thermistor, (2) the circuitry used to measure the thermistor resistance, (3) the calibration and equation used to convert measured resistance to temperature, and (4) the aging and resulting drift of the sensor over time. Thermistors are typically calibrated to correct for variations due to (1) and (2).

About 10 to 20% of the boreholes are visited once per year and measured using single thermistors and a data logger. In this case the system is routinely validated in an ice-bath allowing correction for any calibration drift. The accuracy of an ice-bath is ~± 0.01 °C. Using the offset determined during this validation to correct the data greatly increases the measurement accuracy near 0 °C, an important reference point for permafrost. The remaining systems are permanently installed and typically ice-bath calibrated at 0 °C before deployment. The calibration drift is difficult to quantify as thermistor chains are not frequently removed for re-calibration or validation. In many cases removal of thermistor chains becomes impossible some time after deployment, e.g. because of borehole shearing.

The drift rate among bead thermistors from different manufacturers was <0.01 °C per year during a 2 year experiment at 0, 30, and 60 °C. The calibration drift of glass bead thermistors was found to be 0.01 mK per year, at an ambient temperature of 20 °C. A single drifting thermistor in a chain is detectable through its anomalous temporal trend. Such data are excluded from final data sets.

The above discussion of accuracy relates to the absolute temperature values measured, but the detection of temperature change is more accurate because errors in calibration offset have no impact, sensor nonlinearities are generally small and not of concern. We therefore consider

<0.1 °C a conservative average estimate of the accuracy of temperature change on an individual sensor basis.]

sensor depth accuracy - estimated impact on measurement depth +- 2 cm [The absolute accuracy of borehole temperature measurements, in terms of their representativeness of the temperature distribution in undisturbed soil, also depends on the depth accuracy of the sensors' positions in the borehole. GTN-P is establishing standard protocols for measurement depth accuracy but up to date there still exist different definitions of depth of measurements and there is a variety of temperature sensor geometries].

location accuracy - estimated impact on location +- 200 m [The absolute accuracy of the location of the borehole temperature measurements, in terms of their representativeness of the land surface, depends on the accuracy of the coordinate pair that is provided by the Principal Investigator (PI).

However, both data collections, GTN-P and ROSHYDROMET contain a considerable large percentage of misplaced coordinates sometimes kilometres apart dependent on region/data author. Checking each borehole by hand and if necessary, correction of coordinates seems necessary. This inaccuracy is for a large part due to PI entries of decimal coordinates with only two decimal places. Up to date we are contacting data authors, providers and NSIDC about the correct geolocation. Already for several sites the location could be adapted with the help of data authors/providers. The estimated accuracy of +- 200 m refers to a conservative estimate of the final corrected data set.]

For Permafrost ECV Active Layer Thickness we provide conservative estimates on

Thaw depth accuracy – estimated impact on thaw depth 0.02 m

[Thaw depth is an essentially instantaneous value that is always less than or equal to the thickness of the fully developed active layer. Probing of the active layer is performed mechanically with a graduated rod. The typical probe is a 1 m long stainless-steel rod. The probe rod is inserted into the ground to the point of resistance. A distinctive sound and feel is apparent when ice-rich frozen ground is encountered. At sites where thaw depth is very large (e.g., 1-3 m), it is very difficult, however, to extract a probe in deeply thawed soils, or stony soils. Optimally executers should have experience with this measurement and body strength].

active layer thickness accuracy– estimated impact on active layer thickness 0.05 m

[Nelson and Hinkel, (2003) (in Methods for measuring active-layer thickness. In: A Handbook on Periglacial Field Methods) highlight that the term of thaw depth is distinct from the term of active layer thickness. The permafrost ECV active layer thickness is used in reference to the maximum development of the thawed layer, reached at the end of the warm season. This is distinct from the term active layer depth referring to the thickness of the thawed layer at any time during its development in summer.

Active Layer thickness is usually measured on grids of 10, 100 or 1000 m with evenly spaced nodes at 1, 10 or 100 m (IPA 2008). Fagan and Nelson (2017) showed, that a systematic stratified unaligned design has advantages over a systematic design, but that the inaccuracy of a systematic design is only small in comparison stratified unaligned design. Active-layer thickness can vary substantially on an interannual basis. In general, it is greater in years with warmer summers and thinner in those with cooler temperatures (Brown et al., 2000).

For an estimation of the ECV active layer thickness it is relevant to measure active layer depths in the grid at the end of the thawing season (https://www2.gwu.edu/~calm/data/north.html). For some measurements in the CALM data collection, metadata information is provided if a value was measured earlier during a year. These measurements will be discarded from the validation data set on Active Layer thickness and moved to an additional validation data set on Active Layer thaw depth at specific times within the unfrozen season.]

location accuracy of CALM measurement grids - estimated impact on location of the grid center and or corners: +- 5 m

accuracy of single-point thaw depth measurements on expeditions - estimated impact on location of the grid center and or corners: +- 10 m

[The absolute accuracy of the point location of the thaw depth measurements carried out on expeditions is estimated using common GPS inaccuracy and measurement problems at high latitudes compared to the annually revisited CALM grid that always allows refinement of the coordinate measurement of the location.]

3 METHODOLOGY TO DETERMINE UNCERTAINTIES

This section outlines the methods used in Permafrost_cci to characterize uncertainties of the permafrost ECV product. As primary source for uncertainty assessment, we will use the extensive data base of in-situ observations of annual average ground temperatures and active layer thickness. The skill of the algorithms is assessed through measures such as correlation, root mean square error and standard deviation. These global uncertainties are highly useful to inform the permafrost and climate modeling communities in the tradition of the global data sets provided by the ESA DUE GlobPermafrost project. Instead of comparing ensemble averages of ground temperature and active layer thickness to in-situ measurements, we will explore methods to identify the best-fitting ensemble member. This will mainly rely on a landcover assessment for the individual borehole sites but could also take the date of final snow disappearance at the borehole sites from measurements at the boreholes into account, thus allowing to select the best-fitting ensemble member. This way, the scaling problem between the e.g. near-point measurements at boreholes and the 1km Permafrost ECV products can be strongly moderated, which has the potential to improve the uncertainty characterization.

Furthermore, we provided a first-order estimate for pixel-by pixel uncertainties by providing the spread (root mean square error – RMSE) of the model ensemble for the 1km pixels of the Permafrost_cci products that is likely a useful measure for many users Another possibility for calculating pixel-by pixel uncertainties would be to apply multivariate regression of the obtained mismatches using both input data sets and the modeled ground temperature and active layer thickness. In doing so, one for example could expect to obtain larger uncertainties when snow depths are low, as it is the case in e.g. the GlobPermafrost ground temperature product. The main challenge with this method is to obtain a sufficient statistical sample with the available in-situ data. We have tested this procedure in years 2 and 3 of Permafrost_cci, but the results suggest that the statistical sample is indeed too small to compile a statistically significant multi-variate regression model. We will continuously update the method on uncertainty evaluation, in response to improvements of the processing chain and the data basis for evaluation provided by the users.

4 ACCURACY TO BE REPORTED

The following uncertainties will be reported:

- RMSE in °C for the ensemble mean of annual average ground temperature
- RMSE in cm for ensemble mean of active layer thickness

The assessment of permafrost extent is in first place limited by the number N of ensemble members modeled which limits the precision to 1/N. For seven ensemble members, the precision of the permafrost extent is 0.14 [-]. The uncertainty of the permafrost extent product will then be determined from the RMSE of the ground temperature and the ground temperature distribution within the ensemble. If the maximum temperature within the ensemble is -8°C, for example, and the RMSE is 2.5°C (see previous section), the uncertainty in permafrost fraction will be practically zero, since all model realizations still show permafrost even when adding a potential error.

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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