CCI+ PHASE 1 – NEW ECVS
PERMAFROST

D1.3 DATA ACCESS REQUIREMENTS DOCUMENT (DARD)

VERSION 2.0

22 DECEMBER 2020

PREPARED BY

Document Status Sheet

Issue	Date	Details	Authors
1.0	15.01.2019	First year version	AB, CP, BH, MW, CB, RD, CK, SW, TS
1.5	23.11.2020	Update of LST_cci, Snow_cci and reanalyses data	SW
2.0	22.12.2020	Update of ground temperature and active layer thickness datasets 1997 to 2018, new Version 2 including interpolated ground temperature data in shallow depths. New table 4.9 including PIs	BH, MW, SW, AB

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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.

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EXECUTIVE SUMMARY

The Data Access Requirement Document (DARD) identifies all of the required input data, both satellite and auxiliary, for product generation and validation. The DARD also describes the conditions under which these data are made accessible. Accordingly, each data description contains information on key technical characteristics, about data availability and coverage (time-scale, geographic, temporal).

In year 3, we will produce an additional demonstrator product based on land surface temperatures from ESA Temperature_cci, snow extent from ESA Snow_cci and landcover information from ESA Lancover_cci. This demonstrator product will only be available for selected regions.

Permafrost_cci level 4 products are created from the analysis of lower level data, resulting in gridded, gap-free products. The initial input satellite data products are MODIS Landsurface temperature and ESA CCI landcover data. Gap filling relies on ERA5 Reanalyses data. Auxiliary data include information on terrain, landcover and soils, which are used for model parameterization. This includes global as well as regional datasets which are publicly available.

The main source for validation with in situ data is the Global Terrestrial Network for Permafrost (GTN-P) managed by the International Permafrost Association (IPA). GTN-P/IPA established the Thermal State of Monitoring (TSP) and the Circumpolar Active Layer Monitoring program (CALM). Further suitable records come from national and regional networks such as ROSHYDROMET in Russia and PERMOS in Switzerland. Borehole time series provide climate research data sets, however no easy-to use time series depth data that are data fit for validation and round robin exercises. Needed are standardized and corrected time series on mean annual ground temperature, across the vertical profile from shallow to deeper borehole depths. The depth stratification of synthesised time series depths data was optimized according to the availability of data sensors in depths specific to GTN-P and ROSHYDROMET.

The best visual expression of mountain permafrost is represented by rock glaciers, which, in contrast to the permafrost itself, can be mapped and monitored directly using remotely sensed data. Several regional databases of rock glaciers exist, including the Permafrost Information System of ESA DUE GlobPermafrost. While efforts have been carried out to produce reliable inventories during the GlobPermafrost programme, standardisation is still needed. These inventories are partially extended within Permafrost_cci. Freely or to the consortium available maps based on traditional methods provide an additional data type for evaluation.

1 INTRODUCTION

1.1 Purpose of the document

The parameters required by the Global Climate Observing System (GCOS) for the Essential Climate Variable (ECV) Permafrost are **Active Layer Thickness** (the maximal seasonal thaw depth) and **Permafrost Temperature**. ESA Permafrost_cci will provide the **ECV product Permafrost Temperature** and **Permafrost Active Layer** and in addition **Permafrost Extent** derived from 2 m depth temperature results.

This document details the requirements towards global satellite products as well as other datasets needed for model parameterization and validation.

1.2 Structure of the document

Chapter 2 provides information on all the data that are needed as input for the production of the ECV satellite product Permafrost Mean Annual Ground Temperature (MAGT), Permafrost active layer thickness as well as Permafrost Extent. Chapter 3 gives an overview on the validation data from GTNP/TSP in lowland permafrost areas and GTN-P/TSP PERMOS ground temperature data sets. This chapter also provides the overview on temporal and geographical coverage of the usable GTN-P and ROSHYDROMET time series for Permafrost_cci. Chapter 3 describes available data from the PERMOS Mountain Permafrost Rock Glacier Inventory and on the collection of permafrost maps suitable for validation.
A summary of the attributes of the data required to generate and validate the Permafrost_cci products is provided in chapter 4.

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

[RD-4] Bartsch, A., Westermann, Strozzi, T., Wiesmann, A., Kroisleitner, C. (2019): ESA CCI+ Permafrost Product Specifications Document, v2.0

1.5 Bibliography

A complete bibliographic list that support arguments or statements made within the current document is provided in Section 6.1.

1.6 Acronyms

A list of acronyms is provided in section 6.2.

1.7 Glossary

The list below provides a selection of terms relevant for the parameters addressed in Permafrost_cci [RD-5]. A comprehensive glossary is available as part of the Product Specifications Document [RD-4].

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.
REFERENCE: van Everdingen, 1985 5

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 DATA REQUIRED FOR ECV PRODUCT GENERATION

2.1 Satellite derived land surface temperature

Daily 1km MODIS LST data sets from 2003-2018 based on the level 3 version 006 collection (products MOD11A1 and MYD11A1) have been employed. These data are based on acquisitions of two satellites, Terra and Aqua, which in total provide four measurements per day for cloud-free conditions (two day and night retrievals each). To be employed for permafrost assessment, periods with cloudy conditions must be gap-filled. For this purpose, we use near-surface fields of the ERA5-reanalysis (see section 2.5), using the algorithm applied in ESA GlobPermafrost with ERA-interim data to gap-fill LST data (Westermann et al., 2015, Obu et al., 2019). MODIS LST is provided freely by NASA Land Processes Distributed Active Archive Center (LP DAAC) and feature a doi-number. The required data are readily downloaded at the University of Oslo and available for processing at its Saga Supercomputing facility.

For the demonstrator product, MODIS LST will be replaced by multi-mission Level-3 products of LST for the period 2003-2019 produced by LST_cci (release expected in January 2021).

2.2 Snow information

For the demonstrator product, we expect to use snow extent data made available the ESA Snow_cci project. This will in particular help constraining the onset of the thaw season and thus has the potential to improve the representation of active layer thickness in Permafrost_cci (similar to Westermann et al. 2017).

2.3 Land cover including water mask

Land cover information is required to define soil properties and snow redistribution (Westermann et al. 2015). The current Landcover_cci dataset, though featuring severe shortcomings for this task (Bartsch et al. 2016a), but will be used. C3S Landcover will be also considered in case it becomes available for permafrost regions.

2.4 Soil stratigraphy

External soil datasets developed for the Arctic (e.g., NCSCD, Hugelius et al. 2013, C-band SAR proxies as in Bartsch et al. 2016b and Reschke et al. 2012) as well as Landcover_cci information have been combined to aid parameterization of the permafrost model (e.g. by defining porosity). The Northern Circumpolar Soil Carbon Database version 2 (NCSCDv2), a spatial dataset created for the purpose of quantifying storage of organic carbon in soils of the northern circumpolar permafrost region. The NCSCDv2 contains information on fractions of coverage of different soil types as well as storage of soil organic carbon between 0–300 cm depth. The NCSCDv2 is available either as a polygon-based database or converted to gridded data. Gridded data products are available in different spatial grid resolutions and in formats adapted for use in desktop GIS-applications and model applications. The dataset is freely distributed by the Bolin Centre for Climate Research. Datasets with additional details on wetlands have been incorporated. Global datasets of wetlands are of too coarse spatial resolution and lack thematic content required for permafrost regions (e.g. Reschke et al., 2012).

Global datasets of near surface soil moisture such as Soilmoisture_cci are also not applicable due to too coarse spatial resolution, data gaps in the boreal region, impacts of waterbodies in the Arctic (e.g. Högström and Bartsch, 2017) and too low thematic accuracy (RMSE ~0.16 m^3/m^3 for passive and combined; ~0.11 m^3/m^3 for locally matched ASCAT (Högström et al. 2018)). Proxies for wetlands (and also soil organic carbon content) are, however, regionally available from SAR at the required spatial resolution. They have been developed within the ESA ALANIS Methane (2010-2012), FP7 PAGE21 (2011-2015) and ESA DUE GlobPermafrost projects. Datasets are freely available via PANGAEA.

2.5. Reanalyses data

As LST_cci will target significant resources to improve cloud detection, a significantly improved performance with a lower number of cloud-contaminated and thus biased LST retrievals is expected. Nevertheless, gaps due to prolonged cloudiness will remain which will to be gap-filled with reanalysis data (see above, Westermann et al., 2015; 2017). For Permafrost_cci, the new ERA-5 reanalysis has been employed, with this new higher-resolution product presenting significant advantages over previous generations of reanalyses. Furthermore, reanalysis data of precipitation have been employed to generate time series of snow depths for each pixel. In years 2 and 3, reanalysis data have also been used to prolong the LST time series prior to 2003 which is required for model spin-up (Westermann et al., 2017), using pixel-wise statistical downscaling following Westermann et al., (2015).

From the ERA-5 reanalysis, the surface fields for air temperature, precipitation, geopotential and wind speed are required, as well as air temperature, wind speed and geopotential at the pressure levels 800, 700, 600, 500, 400, and 200mbar.

2.6. DEM

A global digital elevation model is required which includes the Arctic and provides sufficient spatial resolution. The 1 km Global Multi-resolution Terrain Elevation Data 2010 (GMTDEM) complies to these requirements. It is based on several satellite derived Digital Terrain Elevation Datasets, including the SRTM and altimeter data and distributed by the USGS.

PRODUCT VALIDATION

Special emphasis for the Permafrost_cci product is placed on product validation with data from international and national permafrost monitoring networks and in cooperation with the permafrost community. 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 Monitoring (TSP) and the Circumpolar Active Layer Monitoring program (CALM) (Brown et al., 2000), including standards for measurements and data collection (Clow 2014). The need for the development of a suitable benchmark dataset has been stressed by users, as it does not exist yet to date [RD-1,2,3]. To validate the Permafrost_cci products, we collected ground monitoring data from various national and international monitoring programs such as GTN-P/IPA and ROSHYDROMET, and repositories in which measurement programs and PIs deposited data collections, such as the National Science Foundation repository NSF (US), the Earth and Environmental data repositories PANGAEA (DE), and NORDICANA-D (CA). This comprehensive data collection includes variable timeframes from hourly over annually to sporadic measurements and covers a wide range of different vegetation and permafrost types, however with incomplete data as well as metadata coverage and a considerable large percentage of misplaced coordinates which mostly relates to older boreholes and depend on the regions or Principal Investigators (PIs)

The validation and evaluation efforts innovatively consider high-mountain permafrost regions, using in-situ observations of ground temperatures, changes in subsurface ice and unfrozen water content, and velocities of permafrost creep, provided by national data-services such as GTN-P PERMOS in Switzerland. The PERMOS data and the ESA GlobPermafrost rock glacier inventory support the validation of Permafrost_cci products in mountain areas, where the Permafrost_cci products contain the highest uncertainties.

3.1 Overview of in-situ data

3.1.1 Permafrost and stratigraphy in-situ datasets

Ground data for the validation of ECV terrestrial permafrost are managed and made publicly available at no costs via large-scale international and regional programs where several of the team members are in close cooperation with. GTN-P together with the Arctic Portal provides a dynamic GCOS GTN-P database for upload and download of data containing CALM and TSP data in the Arctic, Antarctic, Central Asia and mountain regions. The national monitoring networks also sustain national databases and portals for downloading data, such as GTN-P PERMOS in Switzerland. The validation and evaluation efforts innovatively consider high-mountain permafrost regions, using in-situ observations of ground temperatures, changes in subsurface ice and unfrozen water content, and velocities of permafrost creep.

The Geophysical Institute Permafrost Laboratory, GIPL, University of Fairbanks, Alaska, led by Prof. Romanovsky, manages large parts of the GTN-P measurement sites in Alaska and several sites in Eurasia. The download of the complete high-quality GIPL dataset – borehole temperature, soil temperature and air temperature data functions via the National Science Foundation (NSF) Arctic Data Center. For Canadian datasets, Nordicana D is the data repository of the Canadian Centre d'études Nordiques (CEN). Nordicana D curates long-term time series of permafrost borehole temperatures, and also hosts and publishes datasets of shallow ground and air temperature in high temporal resolution that are not in full extent part of the GTN-P database. The TSP Norway online database (http://www.tspnorway.com) lists measurements of ground temperatures on Svalbard and in Norway in a WebGIS framework. Several permafrost observatories are set up along the Western Antarctic Peninsula from the South Shetlands to Palmer archipelago and maintained by the universities of Lisbon and Alcalá de Henares in cooperation with various partners (e.g., Univ. Wisconsin-Madison, Argentinean Antarctic Institute, Federal University of Viçosa). The most relevant datasets of these national networks are also contained in the global GCOS GTN-P database. ROSHYDROMET is the national Russian meteorological monitoring network providing long-term ground temperature records close to meteorological stations. Permafrost_cci is compiling these ground temperature records from the measurement programmes GTN-P and ROSHYDROMET (RHM), and further national permafrost data sets from the repositories NSF and PANGAEA and from individual PIs of the Permafrost research community. While the GTN-P data that we compiled are downloaded in late 2018, there was no further data input in the dynamical GTN-P data base and we obtained the new records directly from GTN-P PIs. These data provided to Permafrost_cci are not yet available in the dynamical GTN-P database as of this date in December 2020.

Table 1: *Ground data for sub-ground thermal properties planned in Permafrost_cci*

<table>
<tr><th>Region</th><th>Data on ground temperature, air temperature, active layer</th><th>Contributor</th></tr>
<tr><td>Circumpolar Arctic and Antarctica</td><td>temperature data (borehole, soil, air), active layer depths, several decades for some sites</td><td>TSP, CALM, NSIDC,
dynamic GCOS GTN-P database</td></tr>
<tr><td rowspan="2">North American Permafrost Regions</td><td>temperature data (borehole, soil, air), active layer depths, several decades for some sites</td><td>GIPL/UAF published in NSF Arctic Data Centre, NSIDC, dynamic GCOS GTN-P database</td></tr>
<tr><td>temperature data (borehole, soil, air) active layer depths</td><td>NORDICANA D,
dynamic GCOS GTN-P database</td></tr>
<tr><td>Siberian Permafrost Regions</td><td>temperature data (borehole, soil, air) active layer depths</td><td>GIPL/UAF published in NSF Arctic Data Centre, NSIDC, dynamic GCOS GTN-P database, CALM online, ROSHYDROMET</td></tr>
<tr><td>European high-latitude Permafrost Regions</td><td>temperature data (borehole, soil, air)</td><td>TSP-Norway online database, ROSHYDROMET</td></tr>
<tr><td>Antarctic Permafrost Regions</td><td>temperature data (borehole, soil, air)</td><td>dynamic GCOS GTN-P database, NSIDC</td></tr>
</table>

Stockholm University, SU, compiled the extensive frozen soil sample archive from sites across the northern permafrost region. This includes several thousand individual soil samples from hundreds of locations spread across Russia, Greenland, Svalbard, Fennoscandia and Canada.

3.1.2 GCOS GTN-P temperature data collections

The GCOS GTN-P data collection (described in Biskaborn et al., 2015, 2019) is accessible via http://gtnpdatabase.org/boreholes and comprises 1360 sites with metadata entries, when accessed in November 2018 (Table 2, Figure 1, various filters like elevation or depth range, permafrost zone or responsible person can be applied, to generate subset data collections).

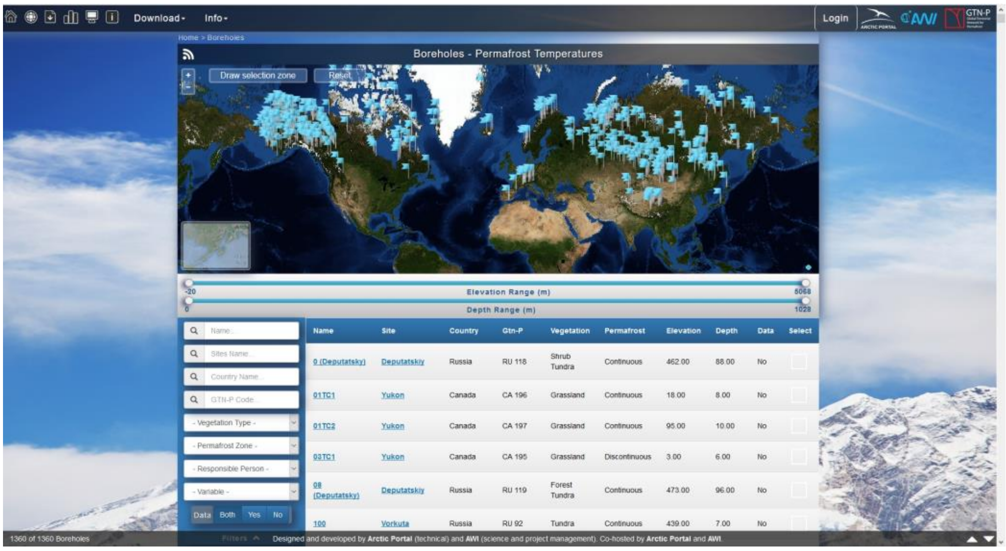

Figure 1: *Screenshot of the GTN-P data portal with various filtering opportunities (http://gtnpdatabase.org/boreholes)*

When accessed in November 2018, 485 sites of the dynamical GCOS GTN-P database contained measurement datasets, of which 113 were satellite-derived DUE Permafrost products on LST and Surface Moisture and not in-situ temperature data. Further on, there were technical problems with download of empty data sets leaving 369 GTN-P data sets (Table 2).

Not all GTN-P sites are located within the permafrost zone, there is a specifically a large share of borehole data in Russia, Russian-Europe and Siberia outside permafrost. We selected a data collection of sites related to Permafrost Zones to determine the data availability. As not all sites have information on the permafrost zone, we used two datasets of permafrost appearance: i) ESA DUE GlobPermafrost Permafrost Probability (Obu et al. 2018), and ii) the Circum-Arctic Map of Permafrost and Ground-Ice Conditions (NSIDC, Brown et al. 2002). A borehole was defined to be over permafrost ground if either it has an NSIDC-Permafrost Extent or if GlobPermafrost Permafrost Probability is >0.1 (10-100 %). 53 GTN-P sites already have the attribution ‘no permafrost’ as permafrost zone and using the permafrost / no permafrost extraction method described above we found an additional number of ten sites that are explicitly located outside the permafrost zones.

Depending on the source of permafrost zone definition, there is an overlap of different permafrost zone types assigned to some of the data. We harmonized the permafrost zone type attribution and included an additional attribute Permafrost_cci ‘permafrost zone type’ that was straight forward to assign using the spatial features of GlobPermafrost Permafrost Probability, Google Earth and the geographical location. With the new attribute Permafrost_cci ‘permafrost zone type’ we grouped the boreholes into different groups of permafrost zones (Table 3). The borehole sites contain datasets with Ground Temperature, Air Temperature and Surface Temperature (Table 4).

Table 2: Overview on GCOS GTN-P borehole data collections, as downloaded in late 2018.

GCOS GTN-P data collections	**No. of boreholes**
GCOS GTN-P boreholes	1360
GCOS GTN-P boreholes containing data	485
GCOS GTN-P boreholes containing measured in situ temperature data	372
GCOS GTN-P boreholes containing measured in situ data without empty datasets	369
GCOS GTN-P boreholes containing measured in situ data without empty datasets in mountain permafrost regions	**35**
GCOS GTN-P boreholes not in mountain permafrost regions containing measured in situ data without empty datasets	334
GCOS GTN-P boreholes not located in the permafrost zone (continuous, discontinuous, patchy, isolated)	63
GCOS GTN-P boreholes containing measured in situ data without empty datasets within the permafrost zone (continuous, discontinuous, patchy, isolated, permafrost probability >0.1)	**270**

Table 3: Borehole records from GTN-P by permafrost zone (GT=Ground Temperature), as downloaded in late 2018.

Definition from	**Permafrost**	**Boreholes**	**Datasets**	**Datasets GT**
Permafrost Extent NSIDC	**C (=Continuous)**	120	194	146
	D (=Discontinuous)	99	142	109
	I (=Isolated patches)	13	14	13
	S (=Sporadic)	15	15	15
	NA	23	26	23
Permafrost Zone (GTN-P)	**Continuous**	138	219	166
	Discontinuous	94	133	102
	Isolated patches	7	7	7
	Sporadic	18	19	18
	Unknown	4	4	4
	NA	9	9	9
Permafrost Probability	**≤1**	97	169	124
	≤0.8	35	53	38
	≤0.6	49	60	52
	≤0.4	38	45	39
	≤0.2	39	47	40
	0	2	2	2
	NA	10	15	11

Table 4: Number of boreholes and datasets with the different temperature measurement variables, as downloaded in late 2018.

Variable	Boreholes	Datasets
Ground Temperature	270	306
Air Temperature	0	47
Surface Temperature	0	38

GCOS GTN-P temperature – overview on spatial availability

The majority of boreholes are in the USA, Russia and Canada (Table 5). Boreholes in France and Italy are set up in the Alps, but are not classed as "Mountain Permafrost" in the meta data attribution. Overall main vegetation type around boreholes is tundra, followed by coniferous forest, shrub tundra and forest tundra (Table 6).

Table 5: *GTN-P countries and boreholes (GT=Ground Temperature), as downloaded in late 2018.*

Country	Boreholes	Datasets	Datasets GT
United States	60	107	72
Russia	167	228	185
Canada	22	35	28
Italy	1	1	1
Svalbard	7	7	7
France	1	1	1
Sweden	8	8	8
Greenland	1	1	1
Antarctica	3	3	3

Table 6: *Vegetation zones represented in GTN-P records (GT=Ground Temperature), as downloaded in late 2018.*

Vegetation_Name	Boreholes	Datasets	Datasets GT
Coniferous Forest	39	46	42
Deciduous Forest	8	13	10
Forest Tundra	37	72	51
Grassland	12	13	12
Polar Desert	7	13	10
Shrub Tundra	38	49	40
Tundra	99	146	108
No Vegetation	11	13	13
Other	19	26	20

3.1.3 GCOS PERMOS GTN-P temperature – overview on data availability

Amongst the 35 GTN-P mountain permafrost boreholes, 27 belong to the Swiss permafrost monitoring network PERMOS. The PERMOS boreholes cover the whole range of typical mountain permafrost landforms (i.e. talus slope, rock glacier, rock walls, mountain crest and summit) (Table 7) and are spatially distributed over the different geographical region within the Swiss Alps (Figure 3). The longest record totalises more than 30 years of observation, whereas the majority of the PERMOS boreholes has between 10 and 23 years of observation (Figure 2). The depth of the boreholes spans from 14m to 100m depth.

In addition to borehole temperatures, the PERMOS network also collects long-term observations of ground surface temperature, permafrost creep velocities, permafrost resistivities and meteorological data in the Swiss Alps.

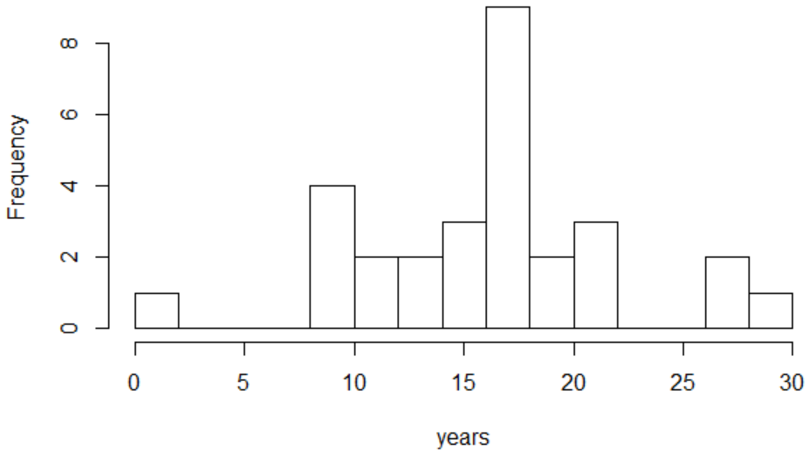

***Figure 2**: Length in years of ground temperature datasets in PERMOS mountain regions*

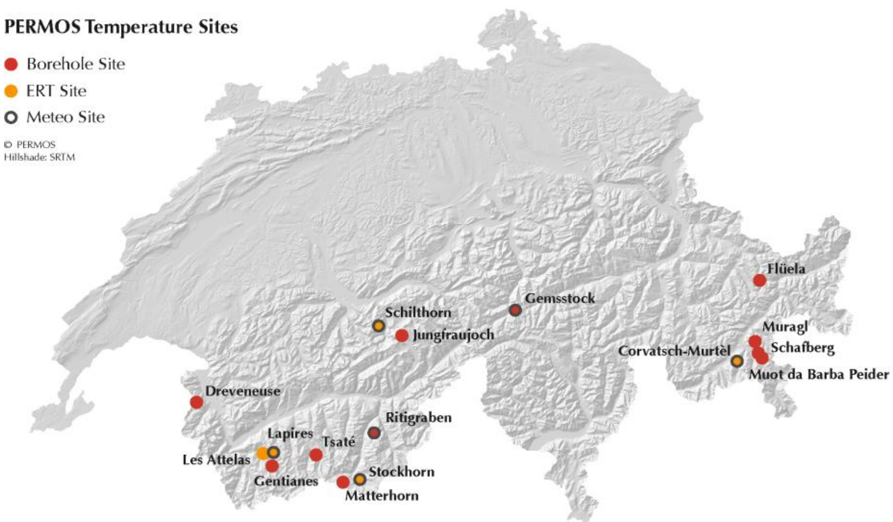

***Figure 3:** Overview on PERMOS borehole and geophysical and meteorological measurement sites.*

***Table 7**: Overview on borehole sites and characteristics in the Swiss National GTN-P PERMOS monitoring program*

borehole	GTN-P	start	lat [DD]	long [DD]	elevation [m]	depth [m]	morphology	surface type	permafrost thickness
ATT_0108	CH 01	2008	46,09677	7,273075	2661	26	talus slope	coarse blocks	>24 m
ATT_0208	CH 02	2008	46,09675	7,273682	2689	21	talus slope	coarse blocks	>20 m
ATT_0308	CH 03	2008	46,0966	7,274924	2741	15	talus slope	coarse blocks	no permafrost
COR_0200	CH 14	2000	46,42853	9,82202	2672	63	rock glacier	coarse blocks	>62 m
COR_0287	CH 13	1987	46,42879	9,821836	2670	62	rock glacier	coarse blocks	>60 m
DRE_0104	CH 04	2004	46,27333	6,889508	1580	15	talus slope	coarse blocks	no permafrost
FLU_0102	CH 05	2002	46,74887	9,943555	2394	23	talus slope	debris	ca. 5 m
GEM_0106	CH 06	2006	46,60125	8,610422	2905	40	crest	bedrock	no permafrost
GEN_0102	CH 07	2002	46,08371	7,302472	2888	20	moraine	debris	>20 m
JFJ_0195	CH 31	1995	46,54611	7,973192	3590	21	crest	bedrock	
LAP_0198	CH 08	1998	46,10612	7,284349	2500	20	talus slope	coarse blocks	>20 m
LAP_1108	CH 32	2008	46,10623	7,284724	2500	40	talus slope	coarse blocks	ca. 15 m
LAP_1208	CH 33	2008	46,10564	7,283808	2535	35	talus slope	coarse blocks	ca. 20 m
MAT_0205	CH 09	2005	45,98232	7,676049	3295	53	crest	bedrock	>53 m
MBP_0196	CH 10	1996	46,4964	9,931076	2946	18	talus slope	debris	>18 m
MBP_0296	CH 11	1996	46,49657	9,93141	2942	18	talus slope	debris	>18 m
MUR_0199	CH 12	1999	46,50757	9,927823	2536	70	rock glacier	coarse blocks	no permafrost
MUR_0299	CH 34	1999	46,50723	9,927338	2539	64	rock glacier	coarse blocks	ca. 18 m
MUR_0499	CH 35	1999	46,50723	9,927703	2549	71	rock glacier	coarse blocks	>15 m
RIT_0102	CH 15	2002	46,17469	7,849835	2690	30	rock glacier	coarse blocks	>13 m
SBE_0190	CH 16	1990	46,49738	9,926302	2754	67	rock glacier	coarse blocks	>16 m
SBE_0290	CH 17	1990	46,4988	9,925215	2732	60	rock glacier	coarse blocks	>25 m
SCH_5000	CH 19	2000	46,55828	7,834426	2910	101	crest	debris	>100 m
SCH_5198	CH 18	1998	46,55828	7,834621	2910	14	crest	debris	>13 m
SCH_5200	CH 20	2000	46,55828	7,834426	2910	100	crest	debris	>100 m
STO_6000	CH 21	2000	45,98679	7,824201	3410	100	crest	debris	>100 m
STO_6100	CH 22	2000	45,98655	7,824057	3410	31	crest	debris	>17 m
TSA_0104	CH 23	2004	46,10905	7,548442	3040	20	crest	bedrock	>20 m

3.1.4 ROSHYDROMET ground temperature data

ROSHYDROMET (RHM) data can be downloaded from http://meteo.ru/data/ (http://aisori.meteo.ru/ClimateR) containing temperature data for shallow sites <=230 cm, snow height and climate data. A number of 458 ROSHYDROMET stations with borehole temperatures are available. As ROSHYDROMET sites are distributed all over Russia with a large percentage not in the permafrost zone, we used the same method that we apply to the GTN-P data to group ROSHYDROMET sites in permafrost and non-permafrost via the datasets DUE Permafrost Permafrost Probability (Obu et al. 2018) and Circum-Arctic Map of Permafrost and Ground-Ice Conditions (NSIDC, Brown et al. 2002). A borehole is defined to be over permafrost ground if either it has an NSIDC-Permafrost Extent or if Permafrost Probability >0.1. Applying our permafrost definitions, a final number of 216 boreholes over permafrost remains (see Table 8)

Table 8: *Borehole records from ROSHYDROMET by permafrost zone, as downloaded in late 2018.*

Definition from	Permafrost	Boreholes
Permafrost Extent NSIDC	**C (=Continuous)**	40
	D (=Discontinuous)	25
	I (=Isolated patches)	54
	S (=Sporadic)	32
	NA	65
Permafrost Probability	**≤1**	46
	≤0.8	13
	≤0.6	18
	≤0.4	52
	≤0.2	73
	0	10
	NA	4

3.1.5 Alaska synthesised near-surface ground temperature data

Wang et al. (2018) synthesised data at 72 soil temperature stations in Alaska, spanning a large range of latitudes from 60.9 to 71.3° N and elevations from near sea level to 1327 m in tundra and boreal forest regions. This data compilation consists of monthly ground temperatures at 0.25 m depth intervals down to 1 m depth, volumetric soil water content, snow depth, and air temperature during 1997–2016. This near-surface ground temperature synthesis permafrost dataset for Alaska (Fig. 4) is based on permafrost monitoring data collected by the USGS, the National Park Services (NPS), and University of Fairbank teams. In the late 1990s, University of Fairbanks (Romanovsky et al., 2015) established a near-surface permafrost monitoring system consisting of 27 stations across Alaska, primarily along the Trans-Alaskan Highway (Fig. 4, triangle symbols). Since August 1998, the USGS has maintained 17 automated stations spanning latitudes (Fig. 9, star symbols) (Urban and Clow, 2017). NPS has monitored ground temperatures since 2004 at several sites in national parks (Hill and Sousanes, 2015) (Fig. 4, square symbols).

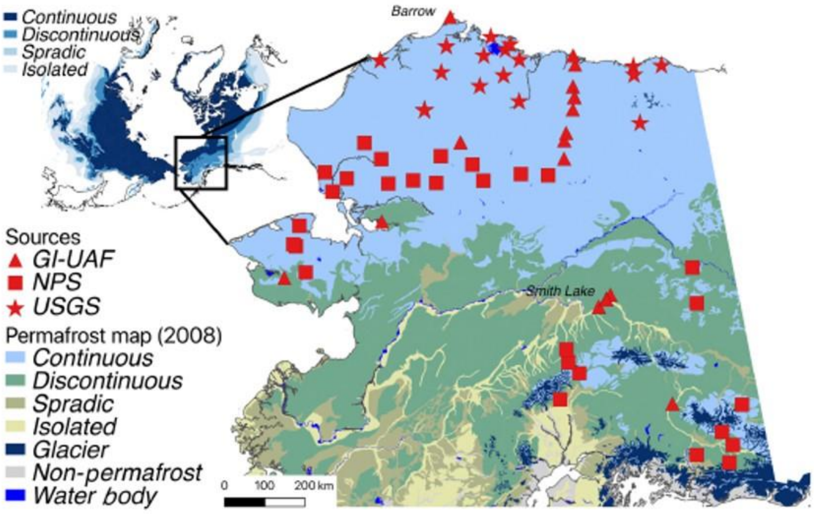

Figure 4: *(Figure 1 in Wang et al., 2018). Locations of the Geophysical Institute at the University of Alaska Fairbanks, USGS, and the National Park Services permafrost monitoring stations in Alaska. The basemap shows the permafrost distribution of Alaska compiled by Jorgenson et al. (2008).*

GIPL University of Fairbanks ground temperature collection contributing to GTN-P: http://permafrost.gi.alaska.edu/sites_map.
NPS ground temperature collection: https://irma.nps.gov/DataStore/Reference/Profile/ and https://irma.nps.gov/DataStore/Reference/Profile/2239061.

Wang et al. (2018) interpolated the discrete measurements at sensor depths down to 1 m depth. For most of the sites, ground temperatures could be extracted at depths of 0.25 and 0.50m (69 and 67 sites, respectively). Ground temperatures at 1m could only be determined at 32 sites, most of which are located in the southern portion of the Alaskan Arctic. This latest compiled synthesis dataset is available at the Arctic Data Center (https://doi.org/10.18739/A2KG55, Wang et al., 2018).

3.1.6 Temperature data collections – accuracy of geolocation

Accuracy issues exist related to the correct geolocation of boreholes in. Some coordinates have been identified to be within rivers, lakes or the sea (Figure 5 shows some examples). Checking each borehole by hand and if necessary correct coordinates was necessary. This inaccuracy is for a large part due to Principal Investigator (PI) entries of decimal coordinates with only two decimal places. We contacted PIs and NSIDC about the correct geolocation and corrected geolocations with their support or based on our best guesses guided by high resolution Google Earth background maps.

Figure 5: *Examples of errors in geolocation of the GTN-P boreholes*

3.1.7 Synthesised ground temperature time series depth data

GTN-P and ROSHYDROMET time series provide climate research data sets, however no easy-to use time series depth data that are data fit for validation and round robin exercises. Although the various datasets contain measured temperature at many different depths, some depths are available at a high frequency (Figs 7, 8). The ‘Alaska shallow’ ground temperature data collection (blue bars) contains already interpolated temperature data at four depths (0.25 m, 0.5 m, 0.75 m, 1 m) for many Alaskan ground temperature soil profiles (Wang, 2018; Wang et al., 2018).

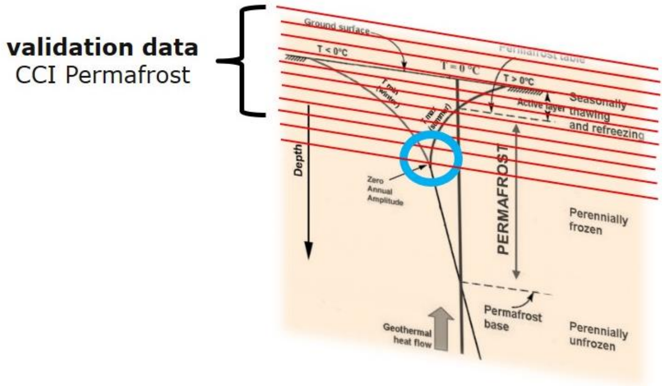

Figure 6: Concept of Zero Annual Amplitude (ZAA) depth and Permafrost_cci depth stratification

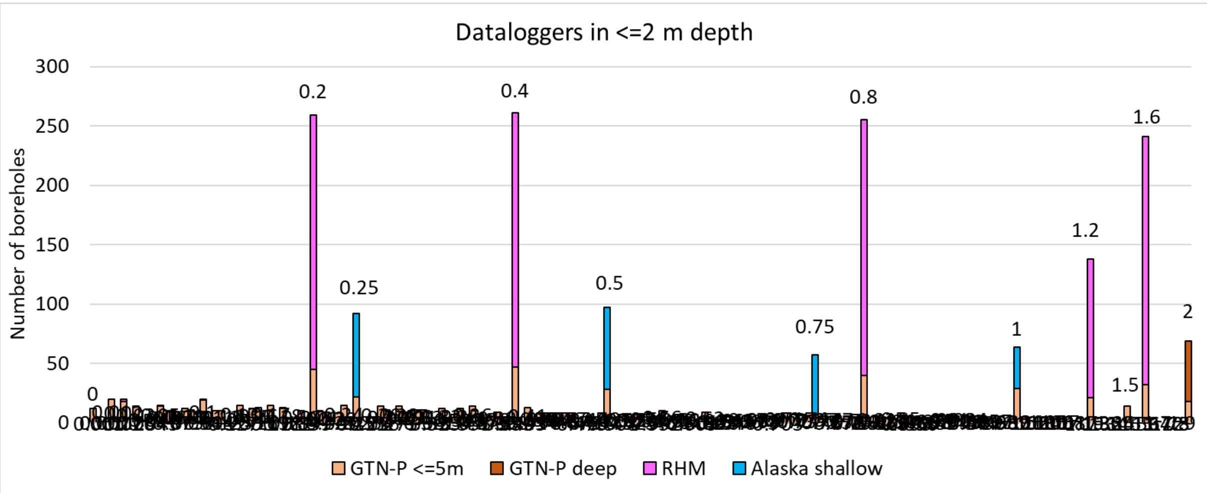

Figure 7: *Number of boreholes/sites (x-axis) with sensors at a given depth (in meter, y-axis). Only sensors in <= 2 m depth are given for GTN-P, ROSHYDROMET and the synthesised Alaska ground temperature data collection (Wang, 2018; Wang et al., 2018). Measurements from temperature sensors in <2 m depth are omitted for deep boreholes (5 m and deeper).*

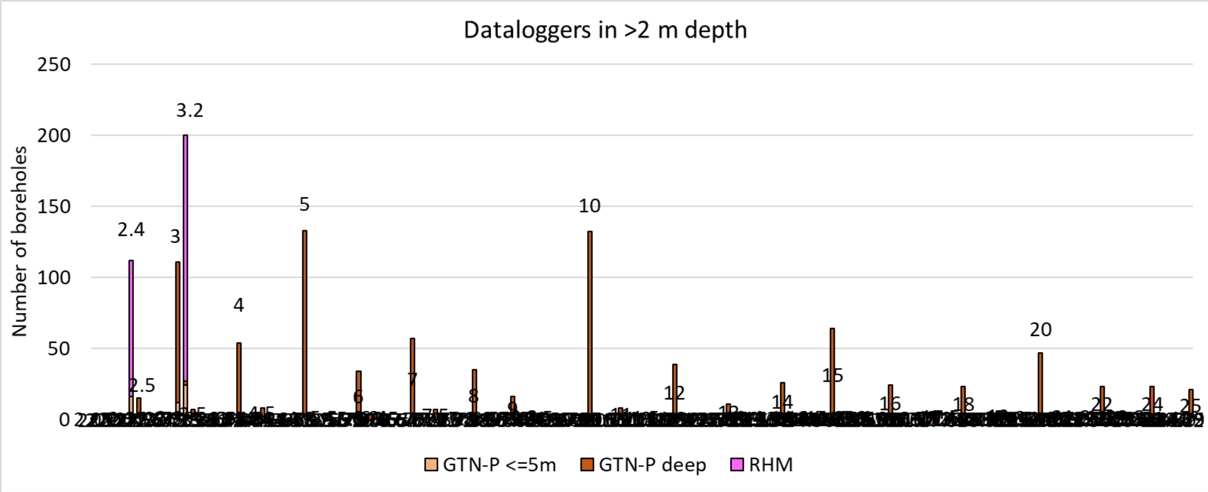

Figure 8: *Number of boreholes/sites (x-axis) with sensors at a given depth (in meter, y-axis). Only sensors in >2 m depth are given for GTN-P and ROSHYDROMET.*

Version 2 synthesised permafrost temperature - discrete depths

Permafrost_cci Match up data set in phase 2, Version 2: standardised ground temperature per depth GTD data with annual resolution from 1997 and 2018 with a circum-Arctic geographic coverage.

This mean annual GTD data set from 1997 to 2018 is compiled from all the discrete depths and time stamps and national and international programs available: depths are at 0, 0.2, 0.25, 0.4, 0.5, 0.6, 0.75, 0.8, 1.0, 1.2, 1.6, 2.0, 2.4, 2.5, 3.0, 3.2, 4.0, 5.0, 10.0, 15.0, 20.0 m. The complete data set has been compiled from

- GTN-P (https://gtnp.arcticportal.org/) [global monitoring programme]
- Roshydromet RHM (http://meteo.ru/data/164-soil-temperature) [national monitoring programme, Russia]
- Nordicana-D [world data repository for Polar research, Canada] (http://www.cen.ulaval.ca/nordicanad/dpage.aspx?doi=45291SL34F28A9491014AFD; Allard et al., 2016, CEN 2013),
- PANGAEA [world data repository for environmental research, Germany] (https://doi.pangaea.de/10.1594/PANGAEA.905233; Boike et. al. 2019; https://doi.pangaea.de/10.1594/PANGAEA.884711, GTN-P 2018, https://doi.pangaea.de/10.1594/PANGAEA.912482, Bergstedt & Bartsch 2020,
- Arctic Data Center [world data repository for Polar research, United States] (https://arcticdata.io/catalog/ #view/doi:10.18739/A2KG55; Wang et al. 2018)
- from individual members of the Permafrost research community (V. Romanovski & A. Kholodov (GTN-P, University of Alaska Fairbanks (UAF), US), M. Ulrich (University of Leipzig, DE)).

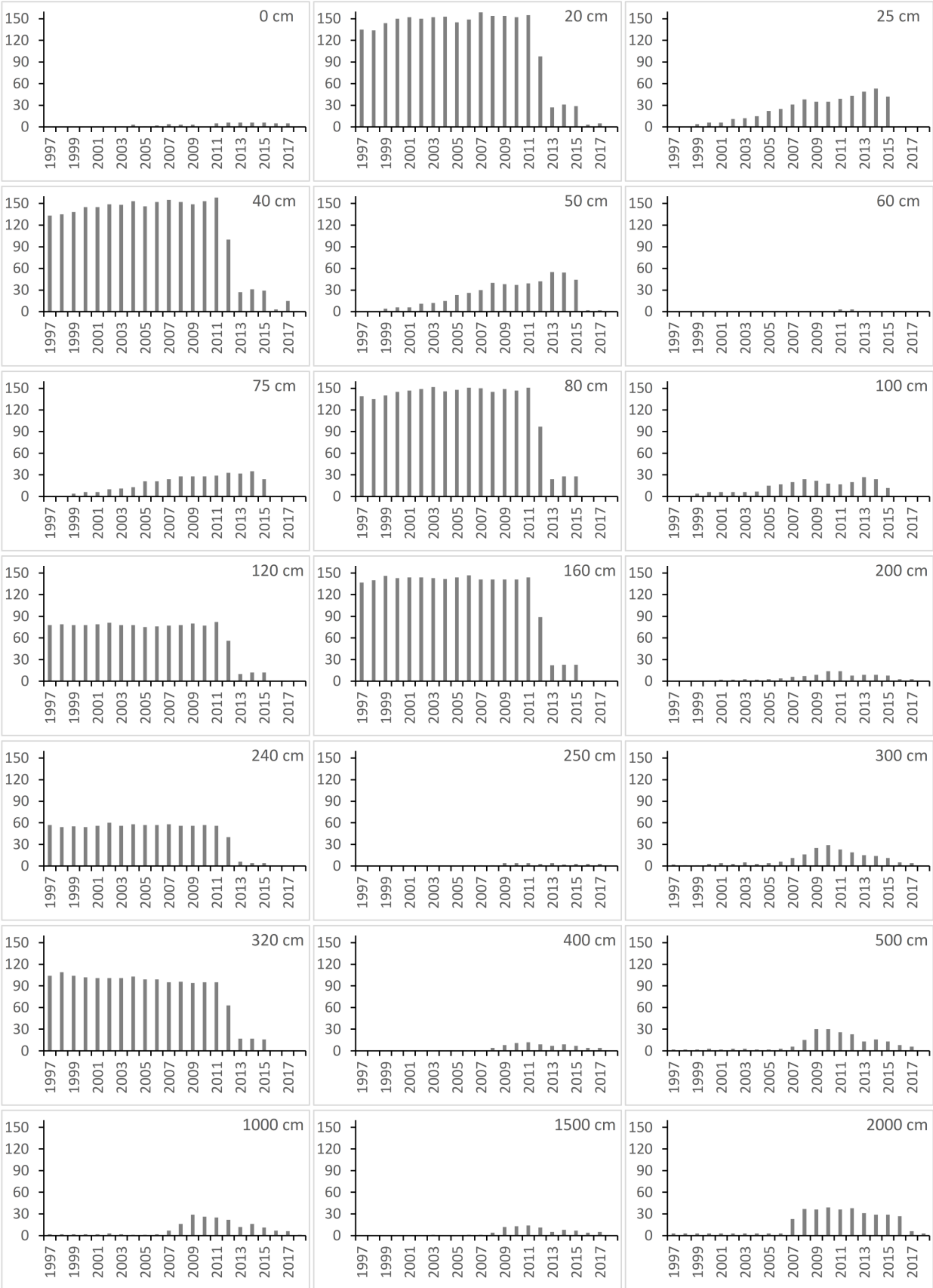

Figure 9: *Amount of datapoints per year and depth in dataset v2(2020)*

***Table 9:** Origin and number of datasets compiled in dataset v2 (2020). C = Continuous Permafrost, d = Discontinuous Permafrost, S = Sporadic Permafrost, I = Isolated Permafrost; classification according to NSIDC map of Brown et al. (2002).*

Source	No.	C	D	S	I	NA
RHM	190	38	22	33	49	48
*PANGAEA	96	28	26	30	1	11
NSF	66	48	17	0	0	1
GTN-P	80	45	25	1	4	5
Nordicana D	5	2	2	0	0	1
**PI Ulrich	2	2	0	0	0	0
***PI Kholodov	13	8	0	0	0	5

*PANGAEA: several sources: ESSD data collections using GTN-P, NSF, USGS
**PI Ulrich M: Uni Leipzig & AWI-Teams, DE
***PI Kholodov A: GTN-P Team V. Romanovsky Uni Fairbanks Alaska, US

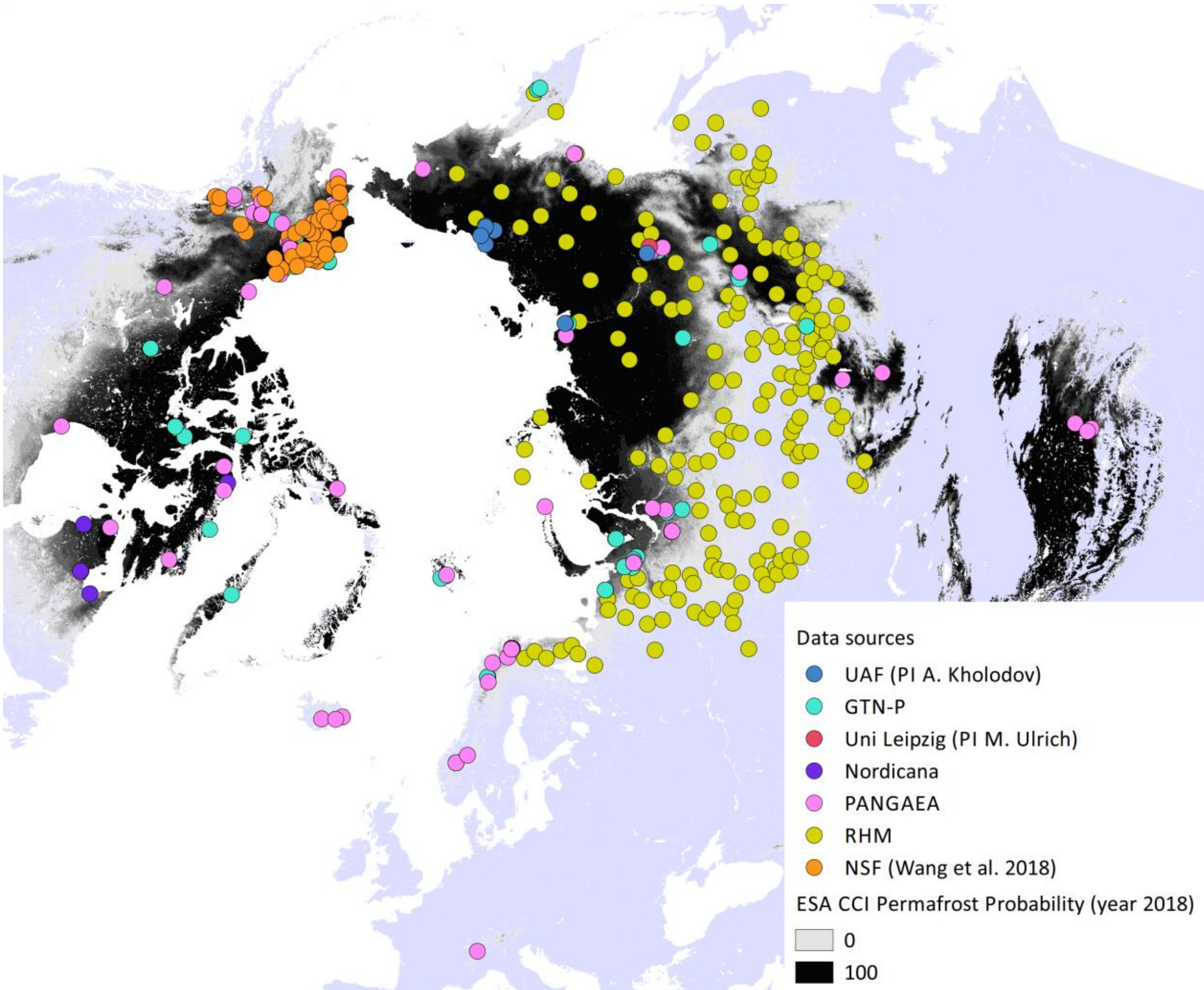

***Figure 10:** Northern hemisphere Permafrost_cci permafrost probability and in situ ground temperature stations of dataset v2 (grouped by data source).*

Version 2 synthesised data set - interpolated depths

As especially the Russian boreholes have only few measurements at exactly 1 or 2 m depth, it is necessary to interpolate temperature values for the Permafrost_cci focus depths (Group III, Figure 11). To achieve this, we only used sites with at least three sensors in the lower depth down to 1.20 m. Separate equations for each sensor-pair and year can be for example obtained by linear regression between two single measurement depths.

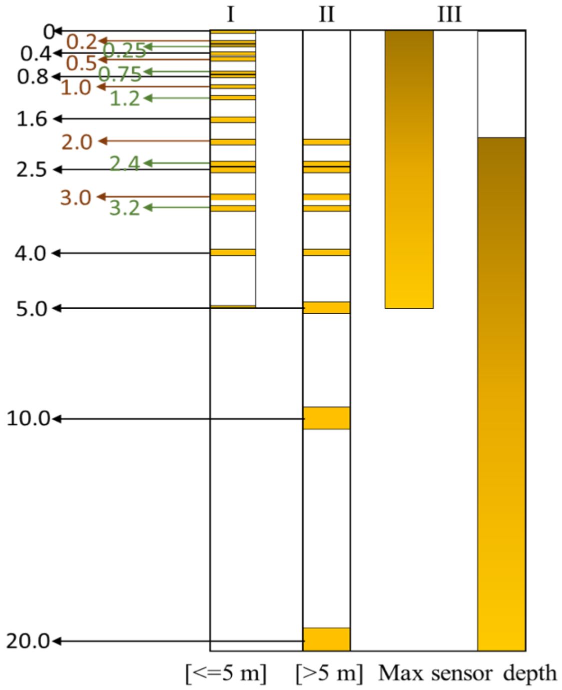

Figure 11: *Discrete depths in version 1 are provided small-scaled in shallower depths and larger scaled in deeper depths. In deep boreholes (Group II, >5 m depth), <1.5-2 m measurements were discarded due to their inaccuracy in large borehole set-ups. Group III temperature data in v2 are interpolated for shallow and deep temperature profiles down to the maximum sensor depth. Also here, the upper 1.5-2 m temperature measurements of deep boreholes are discarded.*

3.2 Mountain Permafrost Rock Glacier Inventory

The best visual expression of mountain permafrost is represented by rock glaciers, which, in contrast to the permafrost itself, can be mapped and monitored directly using remotely sensed data. Rock glaciers are lavastream-like mixtures of permanently frozen debris that creep downslope under gravity. Through their thermal conditions and ice content rock glaciers are sensitive to climatic changes, showing changes in their deformation or motion rates. Changes in rock glacier motion thus indicate changes in mountain permafrost conditions in general. The Mountain Permafrost product of the ESA DUE GlobPermafrost project maps rock glacier deformation in the mountain permafrost regions using repeat optical data and SAR interferometry (Tab. 10).

The produced rock glacier inventories and trends in velocities builds up a unique validation dataset of climate models and permafrost indication maps for mountain regions, where direct permafrost (thermal state) measurements are very scarce or even totally lacking. The information on rock glacier abundance and extent that is since 2017 available by the GlobPermafrost program will support the validation of Permafrost_cci products in mountain areas. In mountain regions the Permafrost_cci products will contain the highest uncertainties due to the known reduced validity or data gaps of the SWE remote sensing product in mountain areas. Rock glacier abundance proves the abundance of high permafrost probability.

Rock glacier and slope instabilities inventories are defined by outlines of the moving zones with an almost homogeneous deformation rate visually inventoried from interferometric satellite images. The extent of each zone detected by the presence of an identified InSAR signal is delimited by a polygon. Polygons are described by their spatial outline, the category of deformation rate and the typology of the related landform. Optional fields related to the reliability of the detection and some remarks are sometimes added. The delineation of a polygon is indicative, the accuracy decreasing significantly in the case of low reliability. While efforts have been carried out to produce reliable inventories during the GlobPermafrost programme, standardisation is still needed. Such inventories will be partially extended within Permafrost_cci.

Table 10: Ground data for mountain permafrost used in DUE GlobPermafrost and expanded in CCI

Region	Data on relief	Contributor
Central Europe Valais, Alps, Switzerland	differential GNSS for Jegi, Dirru, Becs de Besson, Tsarmine rockglaciers since 2010	UNIFR
	continuous GNSS for Jegi and Tsarmine rockglaciers from 2012	UNIFR
	detected DInSAR polygons using DInSAR	UNIFR
	classification for mass movements based on satellite radar data	FOEN
	aerial and terrestrial photographs	SwissTopo
South America Tapado Chilean/Argentinian Andes	annual differential GNNS points	USMB
	rockglacier inventory in Argentina	USMB
North America Atigun Region, Brooks Range, Alaska Disco Island, Greenland	detected DInSAR polygons using DInSAR	UNIFR, GAMMA
	position of frozen debris flows in historic aerial photography	UAF
	ground-based measurements of the frozen debris flow rates	UAF
	rock glacier inventory	GAMMA
Central Asia Tien Shan,Kazakhstan/Kyrg. Himalaya, Kashmir/ Ladakh	rockglacier inventory	UAF, KAZ, HU, GAMMA
	Soviet-Union air photos	KAZ
	rockglacier inventory and high-resolution RS study planned	ICIMOD
Antarctica South Shetland Island	rockglacier inventory	IGOT, GAMMA

3.3 Permafrost Maps

A wide range of permafrost maps are freely available from local to regional modelling as well as mapping in addition to the GlobPermafrost product. This includes:

- GlobPermafrost map on global scale and 1km resolution based on the TTOP approach published by Obu et al. (2018)
- Tienshan in Central Asia is available through GlobPermafrost user agreements with UAF;
- Mongolian Permafrost map based on TTOP approach available through GlobPermafrost user agreements;
- Near-surface permafrost map of Alaska published by Pastick et al. (2015);
- Permafrost map of the Alps published by Böckli et al. (2012);
- Permafrost map of Norway, Sweden and Finland based on TTOP Approach (Gisnås et al., 2017);
- Permafrost map of Tibetan Plateau based TTOP Approach (Zou et al., 2017);
- Geocryological map of Russia and neighbouring republics, 1:2,500,000 scale. Moscow State University, Russian Ministry of Geology. 16 sheets. (available at B.GEOS and AWI).

4 SUMMARY

A summary of the attributes of the data required to generate and validate ground temperature estimates and active layer thickness is given in Table 10 below.

Table 11: *Summary of attributes of the data required to generate and validate Permafrost_cci products*

Data class	Data type	Source	Spatial coverage	Temporal coverage	Repeat periodicity	Availability
Production	MODIS LST	ICESS	global	2000-	<daily	http/ftp
Production	GlobSnow SE & SWE	FMI	Northern Hemisphere			http/ftp
Production	MODIS SE	NSIDC/SSEC	global	2000-	<daily	
Production	ERA5 reanalysis	ECMWF	global	1979-2010	6-hourly	http/ftp
Auxiliary	CCI Landcover	ESA	global	1992-2015	annually	http/ftp
Auxiliary	NCSCD	Univ. Stockholm	NH Arctic permafrost	-	once	http
Auxiliary	ASAR GM wetlands	PAGE21	North of treeline	2005-2011	once	PANGAEA
Auxiliary	ASAR GM SOC	PAGE21	North of treeline	2005-2011	once	PANGAEA
Auxiliary	ASAR WS wetlands	ALANIS Methane	Siberia	2007-2008	twice	PANGAEA
Auxiliary	Sentinel-1/2 landcover	GlobPermafrost	Western Siberia	2016-2018	once	PANGAEA
Auxiliary	GMTDEM	USGS	global	2000-2010	once	http
Validation	TSP ground temperature	GTN-P TSP, PERMOS	irregular	irregular	irregular	gtnp.arctic portal.org/
Validation	CALM active layer depth	GTN-P TSP, PERMOS	irregular	irregular	irregular	gtnp.arctic portal.org/
Validation	RHM	RHM	Russia	1963-2013	daily	meteo.ru/data/
Validation	regional maps	mixed	Alaska , Norway, Sweden, Finland, Canada, Mongolia, Tienshan, Alps, Tibet, Russia	irregular	Single dates	some freely available, others available to consortium
Validation	Velocity measurements	PERMOS	Switzerland	irregular	irregular	some freely available, others available to consortium
Validation	Velocity measurements	Univ. Timisoara	Romania	irregular	irregular	available to consortium

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6.2 Acronyms

AD	Applicable Document
ASCAT	Advanced SCATterometer
ATSR-2	Along Track Scanning Radiometer
AWI	Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research
B.GEOS	b.geos GmbH
C3S	Copernicus Climate Change Service
CALM	Circumpolar Active Layer Monitoring
CCI	Climate Change Initiative
CEN	Canadian Centre d'études Nordiques
DEM	Digital Elevation Model
DUE	Data User Element
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
ERA5	Reanalysis Climate Data
ERA-interim	Reanalysis Climate Data
ESA	European Space Agency
FMI	Finnish Meteorological Institute
FOEN	Swiss Federal Office for the Environment
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GGD	Global Geocryological Data
GIPL	Geophysical Institute Permafrost Laboratory
GI – UAF	Geophysical Institute – University of Alaska, Fairbanks
GMTDEM	Global Multi-Resolution Terrestrial Digital Elevation Model
GNSS	Global Navigation Satellite Systems
GT	Ground Temperature
GTN-P	Global Terrestrial Network for Permafrost
GUIO	Department of Geosciences University of Oslo
HU	Humboldt-Universität, Berlin
ICESS	International Conference on Education and Social Science
ICIMOD	International Centre for Integrated Mountain Development
InSAR	Interferometric Synthetic Aperture Radar
IPA	International Permafrost Association
KAZ	Kazakhstan Alpine Permafrost Laboratory
LP-DAAC	The Land Processes Distributed Active Archive Center
LST	Land Surface Temperature
MAGT	Mean Annual Ground Temperature
maxAGT	maximum Annual Ground Temperature
minAGT	minimum Annual Ground Temperature
MODIS	Moderate-resolution Imaging Spectroradiometer

NCSCD	The Northern Circumpolar Soil Carbon Database
NPS	National Park Service
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
PERMOS	Swiss Permafrost Monitoring Network
RD	Reference Document
RHM	Roshydromet
RMSE	Root Mean Square Error
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SE	Snow Extent
SRTM	Shuttle Radar Topography Mission
SU	Department of Physical Geography Stockholm University
SWE	Snow Water Equivalent
TSP	Thermal State of Permafrost
TTOP	Temperature at Top of Permafrost
UAF	University of Alaska, Fairbanks
UNIFR	Department of Geosciences University of Fribourg
USGS	United States Geological Survey
USMB	Université Savoie Mont Blanc
WMO	World Meteorological Organisation
ZAA	Zero Annual Amplitude
ZAMG	Zentralanstalt für Meteorologie und Geodynamik