Earth Syst. Sci. Data Discuss., 8, 279–315, 2015
www.earth-syst-sci-data-discuss.net/8/279/2015/
doi:10.5194/essdd-8-279-2015

Open Access Earth System Science Data Discussions

The Global Terrestrial Network for Permafrost Database: metadata statistics and prospective analysis on future permafrost temperature and active layer depth monitoring site distribution

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Received: 15 February 2015 – Accepted: 22 February 2015 – Published: 9 March 2015

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Published by Copernicus Publications.

Abstract

The Global Terrestrial Network for Permafrost (GTN-P) provides the first dynamic database associated with the Thermal State of Permafrost (TSP) and the Circumpolar Active Layer Monitoring (CALM) programs, which extensively collect permafrost temperature and active layer thickness data from Arctic, Antarctic and Mountain permafrost regions. The purpose of the database is to establish an "early warning system" for the consequences of climate change in permafrost regions and to provide standardized thermal permafrost data to global models. In this paper we perform statistical analysis of the GTN-P metadata aiming to identify the spatial gaps in the GTN-P site distribution in relation to climate-effective environmental parameters. We describe the concept and structure of the Data Management System in regard to user operability, data transfer and data policy. We outline data sources and data processing including quality control strategies. Assessment of the metadata and data quality reveals 63 % metadata completeness at active layer sites and 50 % metadata completeness for boreholes.

Voronoi Tessellation Analysis on the spatial sample distribution of boreholes and active layer measurement sites quantifies the distribution inhomogeneity and provides potential locations of additional permafrost research sites to improve the representativeness of thermal monitoring across areas underlain by permafrost. The depth distribution of the boreholes reveals that 73 % are shallower than 25 m and 27 % are deeper, reaching a maximum of 1 km depth. Comparison of the GTN-P site distribution with permafrost zones, soil organic carbon contents and vegetation types exhibits different local to regional monitoring situations on maps. Preferential slope orientation at the sites most likely causes a bias in the temperature monitoring and should be taken into account when using the data for global models. The distribution of GTN-P sites within zones of projected temperature change show a high representation of areas with smaller expected temperature rise but a lower number of sites within arctic areas were climate models project extreme temperature increase. This paper offers a scientific basis for planning future permafrost research sites on large scales.

1 Introduction

1.1 Background and motivation

Research on the cryosphere has shown over the last few decades that it has warmed rapidly since the beginning of industrialisation. This warming will probably greatly exceed the global average temperature increase (ACIA, 2004; Groisman and Soja, 2009; Miller et al., 2010; Stocker et al., 2013). Permafrost is defined as ground that remains frozen for at least two consecutive years (Van Everdingen, 1998) and it underlies about one quarter of the Northern Hemisphere landmass, widespread in the Arctic, Antarctic and mountain areas. Further increases in air temperature will induce a warming of subsurface conditions, leading to the thawing of permafrost in some areas. Ongoing permafrost warming (Romanovsky et al., 2010b) and near-surface thawing in permafrost regions associated with rising air temperatures are considered to reinforce warming of the atmosphere through the conversion of the large soil organic carbon pool in permafrost into greenhouse gases, a process termed “permafrost carbon feedback” (Grosse et al., 2011; Hugelius et al., 2013; Schaefer et al., 2014; Schuur et al., 2013). A recent study shows that a global temperature increase of 3 °C could result in an irreversible loss of 30 to 85 % of the near-surface permafrost, with a corresponding release of carbon dioxide between 43 to 135 Gt by 2100 (Schaefer et al., 2014). Monitoring permafrost is essential to understand the impact of climate change on its thermal state and to assess the impact of permafrost thaw on the Earth climate system. Increase of permafrost temperature and thickening of the active layer could also result in substantial effects on northern infrastructure, forcing local, regional and national governments to devise new adaptation and mitigation plans for permafrost regions (Schaefer et al., 2012). This is why permafrost temperature and active layer thickness have been together identified as an Essential Climate Variables (ECV) by the World Meteorological Organization global observing community (http://www.wmo.int/pages/prog/gcos/). The “Permafrost” ECV is monitored by the Global Terrestrial Network for Permafrost (GTN-P), the primary international programme concerned with monitoring permafrost characteristics (Fig. 1). GTN-P, formerly known as GTNet-P, was developed in 1999 by the International Permafrost Association (IPA) with active support by the Canadian Geological Survey (Brown et al., 2000; Burgess et al., 2000) under the Global Climate Observing System (GCOS) and the Global Terrestrial Observing Network (GTOS) of the World Meteorological Organization (WMO). Two components of GTN-P, the Circumpolar Active Layer Monitoring program (CALM) and the Thermal State of Permafrost (TSP) currently serve as the major providers of permafrost and active-layer data (Romanovsky et al., 2010b; Shiklomanov et al., 2012).

1.2 State of the art and research gaps

The GTN-P experienced substantial growth at the beginning of the 21st century. About 350 boreholes for temperature monitoring were established and a considerable amount of active layer depth observations were collected during the 4th International Polar Year (IPY) from March 2007 to March 2009 (Brown, 2010). Efforts of the IPA and the GTN-P at the end of the IPY resulted in reports on the thermal state of permafrost in high latitudes and high altitudes which were called the “IPA snapshot” (Christiansen et al., 2010; Romanovsky et al., 2010a; Smith et al., 2010; Vieira et al., 2010; Zhao et al., 2010).

The growing amount of high-resolution measurements and annual collection of permafrost data clearly prompted the need for comprehensive management of the GTN-P, including its data management system. Several databases exist for particular regions, e.g. NORPERM (Juliussen et al., 2010), a database for Norwegian permafrost data (including Svalbard); and PERMOS, the Swiss Permafrost Monitoring Network (PERMOS, 2013). The permafrost thermal data from the USA is archived with ACADIS (Advanced Cooperative Arctic Data and Information Service), which took over for the former CADIS (Cooperative Arctic Data and Information Service) as a repository for all data from NSF funded Arctic research. A good example for DOI-referenced data publication is Nordicana D, an online data report series of the Canadian Centre d’études Nordiques (CEN), including long-term time-series of permafrost borehole temperatures

(Allard et al., 2014). The Geological Survey of Canada (GSC) also spent great efforts to collect and store thermal permafrost data from the western Arctic, feeding the data into the former GTN-P data management system. The Thermal State of Permafrost (TSP, Brown et al., 2010) and the Circumpolar Active Layer Monitoring (CALM, Shiklomanov et al., 2008) programs oversee the collection permafrost temperature and active layer thickness data from Arctic, Antarctic and Mountain permafrost regions. These programs provide the majority of the content to the GTN-P Database (Fig. 1). Both TSP and CALM provide an online data repository and are actively expanding observational network. However, all existing permafrost repositories so far were conceived as rather static aggregations of data and the modern permafrost community lacks of a dynamic database with the capability to interlink between field scientists in polar research and scientists working on global climate and permafrost models.

1.3 Aims

The long term goal of GTN-P is to obtain a comprehensive view of the spatial structure, trends and variability in permafrost temperature as well as active layer thickness (GTN-P Strategy and Implementation Plan 2012–2016). While the overall aim of the GTN-P Database is to function as an "early warning system" for the impacts of climate change in permafrost regions and provide standardized permafrost data needed as input to global climate models.

In this paper, we introduce the first dynamic database for parameters measured by the GTN-P. The new GTN-P Database is a state-of-the-art tool for storing, processing and sharing parameters relevant to the permafrost ECV measured in the Arctic, Antarctic and mountain regions. It is hosted at the Arctic Portal in Akureyri (Iceland) and managed in close cooperation with the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Potsdam (Germany) and supported by the European Union 7th framework programme project PAGE21.

The specific objectives of this paper are (i) to describe the framework of the GTN-P data management system, (ii) to provide statistics on site distribution in the GTN-P by performing spatial analyses on the metadata; and (iii) to identify spatial gaps in GTN-P by comparing its site distribution with relevant environmental geospatial datasets.

2 Description of the data management system

2.1 Database design and web interface

The GTN-P Database is accessible online at the URL http://gtnpdatabase.org or through the GTN-P website at http://gtnp.org. The general framework of the GTN-P data management system (DMS) is based on open source technologies following an object-oriented data model (Fig. 2) implemented with Cakephp and the database PostGIS, the spatial version of PostgreSQL (Obe and Hsu, 2011). The database distinguishes between permafrost temperatures and annual thaw depths (i.e. active layer depths). To ensure interoperability and enable inter-database search, metadata field names are based on a controlled vocabulary registry. The documentation of the DMS is available and regularly updated on gtnp.org (ISSN 2410-2385) as the database framework and content evolves.

The online interface of the GTN-P Database was developed to maximize usability both for the data submitter and the user of the data products. The resulting roles (data administrator, data submitter and data user) are built into the database providing different rights to read, edit or modify data. Data users can access the database without account and password and have access to (i) permafrost temperatures, (ii) annual thaw depths and (iii) help sections. While administrators have full access and data submitters cannot modify or delete data of third parties. Data not marked as “published” by the data submitters are not accessible to third parties or the public. The help section provides tutorials and template-files for upload and download of borehole temperature and active layer grid data as well as GTN-P maps and fact sheets.

2.2 Data structure and upload

The GTN-P Database is compliant with existing international standards for geospatial metadata ISO 19115/2 and TC/221 (www.iso.org). The database specifically builds on the GTN-P metadata form that was developed as a standard by the GTN-P leadership in 1999 (Burgess et al., 2000). Site metadata must be entered and selected from parameters and properties, which are selectable in dropdown lists in the upload interface. Tutorials and templates of data files provide the necessary information to bring the data into the right CSV format, prior to data upload. The maximum file size for upload is 1.5 MB.

The data upload procedure was conceived to eliminate the need for any prior knowledge of databases by the user. National Correspondents (NC's) from all participating countries were nominated by the national committees and by the scientific international permafrost community to input data on an annual basis, collecting information from the investigators and data managers from that country. NC's are listed on the GTN-P website and can be contacted by permafrost researchers interested in contributing monitoring data to the GTN-P Database. NC's are also encouraged by the GTN-P Executive Committee to pro-actively engage national investigators in the process to ensure a continuous data upload into the system.

2.3 Data search and output

The GTN-P Database features both (i) basic search and (ii) custom search functions. The goal of these functions is to narrow down the number of data records based on a set of criteria. While the basic search is a simple filter by manual character input, the advanced custom search allows the use of multiple search criteria to retrieve a defined list of data records from the repository. The data and metadata associated with the search results can be downloaded by the data user as compressed file packages containing standardized metadata forms in text and XML and the corresponding raw data in CSV (comma separated values) format. However, the CSV format and the in-consistency of the time series, in regards to completeness, frequency and geometry does not allow their direct use within climate models, as they do not comply with the CF 1.6 convention (for Climate and Forecast).

To address this issue, the GTN-P Data Management System processes and aggregates all data on-the-fly through a set of internal functions and Python libraries. All eligible datasets are aggregated into a NetCDF file that has been formatted to catch the geometry of the data. NetCDF (Network Common Data Form) is a set of software libraries and self-describing, machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data.

TSP datasets are linearly interpolated at consistent 0, 1, 2, 3, 5, and 10 m borehole depths. The results are two products in NetCDF format: a TSP dataset of annual time series borehole temperature profiles in an orthogonal relation and a CALM dataset of annual time series of active layer thickness in a time orthogonal template.

Future work focuses on the establishment of data quality control and flags for the data as well as on the conversion of the stations distributed data to a regular grid at locations where the monitoring sites' scattering allows it.

2.4 Data policy

GTN-P follows an open-access policy in line with the IPY data policy. The data management unit of PAGE21 mediates between the GTN-P Database and the PANGAEA Data Publisher for Earth and Environmental Science (Diepenbroek et al., 2002) which provides digital object identifiers (DOI's) for the data products. PANGAEA follows the Principles and Responsibilities of the ICSU World Data System (WDS) and the "Principles and Guidelines for Access to Research Data from Public Funding" established by the Organisation for Economic Co-operation and Development (www.oecd.org). It has also adopted the Creative Commons license procedure, which provides a simple, standardized way to give the public permission to share and use creative work, according to the conditions established by the author.

The GTN-P Executive Committee decided for a general embargo period of one year. This means that data from 2015 will be available at the earliest in 2016 in order to allow investigators the first opportunity to publish their data. For special cases, e.g. doctoral dissertations, this embargo may be extended on demand.

The data will be made freely available to the public and the scientific community in the belief that their wide dissemination will lead to greater understanding and new scientific insights and that global scientific problems require international cooperation. Data download is unrestricted and requires only a free registration needed for web security reasons. Before being able to download data, users must accept the terms and conditions of the data use policy. Therein, the user is asked to contact the site PI's prior to publication to prevent potential misuse or misinterpretation of the data. In addition, an email is automatically sent to the contact person of each dataset downloaded to inform them of the interest in the data.

3 Data quality

3.1 Data sources

A thorough data mining effort was conducted prior to the creation of the GTN-P Database in order to recover as much archive permafrost temperature and active layer thickness data as possible. The recovered datasets were characterized by an extreme diversity. These included global datasets on active layer temperature from the CALM data collection (Shiklomanov et al., 2008), but also datasets aggregated thematically, geographically or institutionally. These other sources include the Advanced Cooperative Arctic Data and Information Service (www.aoncadis.org) at the National Snow and Ice Data Center (http://nsidc.org), the Permafrost Laboratory (University of Alaska, Fairbanks), NORPERM (Juliussen et al., 2010) and PERMOS (PERMOS, 2013), among others. Part of the data was provided by individual permafrost research groups and relayed into the database by the GTN-P National Correspondents.

In addition to GTN-P standard datasets on temperature and active layer thickness, several ancillary existing datasets were opportunistically added to the database. These include in particular remotely sensed land surface temperature and surface soil moisture values that were transferred from ESA DUE Permafrost (Bartsch and Seifert, 2012; DUE-Permafrost-Project-Consortium, 2012).

At the time of submission of this paper the GTN-P Database contained metadata from 1074 TSP boreholes and 274 CALM active layer monitoring sites. 31 boreholes are located in the mountain permafrost regions and 72 in Antarctica. Currently, 277 borehole sites have temperature data and 78 active layer monitoring sites have thaw depth data. Due to the fact that one site can have more than one measurement unit or period, the total number of datasets is 1300, including ground temperature, active layer thickness, surface soil moisture, air temperature, and surface temperature.

3.2 Data quality control

Data being entered into the database undergoes several steps of quality control before receiving approval for data output. To harmonize the different data formats and produce one standard format within the GTN-P Database, every dataset retrieved from external sources underwent a review and if necessary a standardization (“cleansing”) procedure to bring the file into the format needed for upload. This includes in particular conversion of file structures, date formats, reference points and null values. To match the metadata that accompanied older datasets to ISO standards, a set of obligatory metadata information were developed considering the existing metadata forms from the old GTN-P web repository (closed in 2014). Metadata input must be compliant with the database rules and include a number of mandatory fields following the terminology of code lists and control vocabulary associated with the GTN-P Database as documented on the GTN-P website. The interface for metadata input is arranged as drop-down menus that must be completed before the system enables the user to proceed with the data input procedure. In addition to the data quality control of the individual permafrost scientist, the GTN-P Data Management System offers quality control. Successful upload assures correctness and consistency of the dataset. Screening for obvious errors follows with the help of automated data visualization during and after the upload procedure. Interactive and adjustable data plots on the database website serve also as on-the-fly data visualization for scientific purposes.

According to the GTN-P Strategy and Implementation Plan (2012–2016) metadata and data considered for input into the GTN-P Database will be coordinated and reviewed by National Correspondents (NC's) on a regular basis, at least once per year. Datasets are published only after approval by the NC's.

Additionally, overall quality verification is inherently provided by the production of this article. As stated in the online ESSD journal description, the peer-review process this paper went through secures that the involved data sets are (i) plausible without detectable problems, (ii) of sufficiently high quality with clearly stated limitations and (iii) well annotated by standard metadata.

3.3 Quality assessment and limits

In geoscience, errors start to emerge already at the measurement stage. The most common technique of continuously recording borehole ground temperatures at specific depths is the use of permanently installed multi-thermistor cables, providing an accuracy and precision between ca. 0.02 and 0.1 °C (Brown et al., 2000; Romanovsky et al., 2010b). The logger resolution and measurement frequency, however, varies with the type and the depth of the individual borehole. Due to active layer dynamics, the relative vertical position of measurement probes can change and hence introduce an error in the depth indications of old boreholes in sensitive areas. Additionally, the number of vertical positions of sensors varies not only between and within boreholes (and research groups) but also through time. Commonly, sensors are placed every 0.2–0.4 m until 2 m depth, every 0.5 m until ca. 4–5 m depth, every 1–3 m until 15 m depth and in the deeper parts of a borehole sensor are reduced to 5–10 m steps (Brown et al., 2000). As expected, a linear regression on 180 datasets (Fig. 3) indicates that the overall number of temperature sensors increase with increasing borehole depth.

Based on this data, however, the average SD of the number of temperature recordings within a borehole at different dates is 14.0. The maximum difference in the number of measurements between dates is 57. Minimum is 0. The GTN-P Database support group established an IPA action group to develop strategies for profound numerical assessment and control of the GTN-P data quality.

The active layer thickness data (CALM) have generally fewer numbers of potential biases due to the majority of sites performing measurements of summer thaw depths using mechanical probing either in grids or transects resulting in multiple measurements compared to point locations associated with sites using thaw tubes or temperature boreholes. The complex nature of grid metadata, however, created inconsistencies in the structure of the primary data files. Even though the files were standardized before implementation, the low resolution of a number of CALM grid references and TSP borehole coordinates led to imprecise geopositioning; 275 longitudes and 287 latitudes have less than 4 decimal places. 374 datasets had coordinates with decimal degree precision below 4 decimal places of either the latitude or the longitude or both. These datasets have been flagged and will be submitted to the NC's for revision. We assessed the overall metadata completeness for TSP and CALM datasets by calculating the percentage of available fields that are filled in. Figure 4 indicates the percentages of both data types according to the metadata completeness. CALM metadata is generally more complete with values between 50 and 80 % (average 63 %). TSP metadata has a bimodal distribution of completeness with most datasets between 31 and 40 % and a second peak between 61–70 % (average 50 %).

Metadata fields with the most missing information are accessibility, distance from disturbance, bibliographic references, terrain morphology, hydrology, slope and aspect, borehole diameter and permafrost thickness. While these "extra" information are not essential for the direct permafrost monitoring, they are relevant to gain a holistic future view on the thermal state of permafrost by feeding high quality data to global models.

4 GTN-P metadata statistics

4.1 Spatial sample representation of TSP and CALM sites

Table 1 summarizes the distribution of boreholes and active layer monitoring sites per country. The total numbers per country and permafrost zone were calculated by plotting the sites as points and the areas as polygons in ArcGIS. During the analyses some polygons and site coordinates suffered from inaccuracy – e.g. terrestrial boreholes with imprecise coordinates were shown as “offshore” sites. In these cases, land-ocean polygon boundaries were slightly shifted and the land polygons extended to capture the relevant points. For calculating the borehole per area ratios, however, we used the original polygon dimensions.

In order to measure the degree of inhomogeneous sampling and to identify the main geographical gaps, we performed a numerical quantification of the distribution of boreholes and active layer grids in the Northern Hemisphere with the help of a Voronoi Tessellation Analysis (VTA) as suggested by Molkenthin et al. (2014). To reduce the potential bias that result from multiple boreholes or active layer monitoring grids around the same coordinate or which are very close to each other, buffers of 1 km radius for each coordinate were created in ArcGIS. Sites with site-to-site distance of ≤ 2 km were merged and the gravitational centers of the resulting buffer areas were converted to points for further calculations. With the help of this method we reduced 1073 TSP coordinates to 614 buffered TSP sites and 242 CALM coordinates to 187 buffered CALM sites. Voronoi cells were calculated using the Thiessen polygon tool and subsequently clipped to the extension of the IPA map of permafrost zones.

The VTA creates a mosaic by drawing area (cell) boundaries exactly in the middle between neighboring nodes: TSP sites (Fig. 5) and CALM sites (Fig. 6). Every point within a cell is closer to its node than to any other node. Glaciated areas (shapefile from NaturalEarthData, 50 m resolution) were removed from the analysis. In a VTA, uniform distribution of sites would result in maximum peak in the cell size distribution at the same value as $A_{\text{total}}/N_{\text{cells}}$ (Molkenthin et al., 2014), which is basically the same as the mean Voronoi cell size. Hence, to quantify the overall deviation from equidistant sampling of the terrestrial Northern Hemisphere permafrost and glacier-free area, we used the SD of the Voronoi cell size distribution from TSP (SD: 9.08×10^4 km^2) and CALM (SD: 8.68×10^4 km^2). For visualization, we calculated the number of Voronoi cells in a cubic size sequence x^2 (1 to 2, 2 to 4, 4 to 8,..., 1.05×10^6 to 2.10×10^6 km^2) and plotted the results on a logarithmic scale (Fig. 7). Voronoi Cell Size Ranges were attributed to the same colors types as in Figs. 5 and 6. According to the VTA, the TSP cell size distribution peaks two times at smaller values than the $A_{\text{total}}/N_{\text{cells}} = 3.79 \times 10^4$ km^2 indicating a significantly clustered sample distribution. TSP bimodal size distribution is attributed to (i) linear spatial sample configuration along transportation corridors in areas with developed economic and infrastructure as well as several high-density borehole transects and (ii) to the good coverage and high number of boreholes in Alaska, both indicated in green color. The CALM cell size peaks at about the same values as $A_{\text{total}}/N_{\text{cells}} = 1.25 \times 10^5$ km^2. The plateau between 2×10^4 km^2 and ca. 6×10^5 km^2, however, indicates a clustered sample distribution, albeit the panarctic CALM sampling is clustered to a lesser degree than the borehole configuration. High skewness of both TSP (4.99) and CALM (6.52) cell size distributions indicates that the peaks are inclined towards higher cell size values demonstrating inhomogeneous sample distribution.

The boundaries of the bigger Voronoi cells (orange and red) and especially their intersections (Figs. 5, 6 and 9) indicate locations with the highest potential for improving the representativeness of permafrost monitoring from hemispherical or global perspective. However, this statement is based on a purely statistical view of the Northern Hemisphere and is not taking into account disturbing landscape features such as water bodies, forest fires, infrastructure, areas of deforestation, urbanization, farming, mining and wetland drainage.

4.2 TSP borehole depth distribution

We divided the GTN-P borehole depth classes into 1 m bins after Burgess et al. (2000). As Fig. 8 shows, the majority (42.3 %) of all TSP boreholes belong to the surface class

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("SU", < 10 m). In general, there are more shallow (30.6 % "SH", 10–25 m) and intermediate (17.8 % "IB", 10–125 m) than deep boreholes (9.3 % "DB", > 125 m). The peaks in the borehole depth distribution correspond to commonly chosen depths (3, 5, 10, 15, 20, 25 and 30 m). These were often defined prior to drilling to capture specific permafrost features such as the depth of zero annual amplitude (DZAA). Deep boreholes are generally older than shallow boreholes. The average drilling dates (AD) for the GTN-P depth classes are as follows: SU = 2003; SH = 1997; IB = 1993; DB = 1984. The overall average drilling date of boreholes is 1997. However, only 82 % of TSP datasets contain metadata information about borehole ages. The lack of age metadata affects all depth classes. The average borehole depth of datasets without age information is 29 m. The oldest borehole currently present in the database is located in Russia (Vorkuta K-887) and was drilled to 85 m depth in 1957.

4.3 Site distribution compared with soil organic carbon content and vegetation

To identify the main geographical gaps in the distribution of boreholes and active layer monitoring sites, we compared the GTN-P metadata with environmental data from different sources. Permafrost thaw is likely to foster the metabolization of the greatest organic carbon pools in the Northern Hemisphere and is believed to create a positive feedback to the Earth's climate system by releasing enormous amount of greenhouse gases (Grosse et al., 2011; Schaefer et al., 2014). Together with the TSP and CALM Voronoi cell boundaries and simplified permafrost zones, we illustrated the panarctic distribution of soil organic carbon content within the top two meters by using data from the Northern Circumpolar Soil Carbon Database (Hugelius et al., 2013) in Table 2. The distribution of CALM and TSP point coordinates was calculated within the different carbon content groups and shows that, at the circumpolar scale, 25.2 % of all boreholes and almost 29 % of all CALM sites are located in permafrost areas that contain more than 25 % organic carbon. While, only 1.7 % of the boreholes and zero CALM sites cover areas with more than 50 % organic carbon.

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We conducted a similar analysis using vegetation zones. For this, we used the vegetation zone information provided in the original GTN-P metadata. Locations with missing vegetation information were attributed to vegetation zones by using photographs of the site (if available) and/or other sources such as atlases of the local flora. This information is provided in Table 2. Because of the wide variety of sources used to define vegetation zones, we prefer not to base recommendations for future locations of monitoring sites based on this information. However, the treeline (Walker et al., 2005), through its function as a major ecotone between forest and tundra, offers high potential for sensitive recording of climate change signals (Biskaborn et al., 2012) and is therefore shown in Fig. 9.

4.4 Preferential slope orientation

Topography and in particular slope orientation influences the amount of solar radiation received by the ground surface and the accumulation of snow. Due to orbital parameters, in mountainous regions of lower latitudes, permafrost occurs preferably on north-facing slopes in the Northern Hemisphere. Similarly, in continuous permafrost regions, the active layer is usually thinner on north-facing slopes (French, 2007). To inspect the monitoring bias that might be caused by preferential slope orientation, we analyzed the slope and aspect for boreholes and active layer sites.

Only few of the original GTN-P metadata collections contained slopes and aspects of the ground surface at the permafrost borehole or the active layer grid sites. This information also existed in various formats. We used the ESA DUE Permafrost Circumpolar digital elevation model (Santoro and Strozzi, 2012) in ArcGIS to calculate slope and aspect from the Northern Hemisphere topography. This remote sensed derived model, however, has a resolution of 100 m and therefore, the calculated values (in degree units) for each site north of 60° N should be evaluated carefully. Figure 10 shows the slopes and aspects and their statistics for the original metadata and the calculated values in spherical projections plotted with STEREONET 9.2 (Cardozo and Allmendinger, 2013). The graph includes both surface areas at TSP and CALM sites as (i) planes in equal-angle projections and (ii) the frequencies of slope aspects as rose diagrams with a bin size of 30°. A comparison between the original metadata and the DEM-derived values shows major differences in the CALM sites, amplified (i) by the very low amount of slope metadata entries ($n = 8$) and (ii) due to the fact that most active layer monitoring sites are located on a more or less flat terrain. It must be considered, however, that recent CALM sites are usually selected by constant geophysical conditions on flat watersheds and only few historically adapted sites are located on slopes.

The closer the slope values are to zero, the higher the potential uncertainty in the aspect values. Aspects in the original TSP and CALM metadata had various formats including verbal descriptions and abbreviations of main (rough) geographical directions. Accordingly, these rose diagrams and planes are concentrated in categorized directions such as N, NW, WNW etc. A higher overall number of TSP borehole slopes and aspects ($n = 48$) from the metadata than for CALM sites enabled a more reliable comparison between original and calculated values. For all TSP sites north of 60° N, 25 % of the original metadata and 20 % of the DEM derived data rank in the bin between 271 and 300°. Both mean vectors point towards a WSW direction, as indicated in Fig. 10 by the arrows. The fact that slopes at the borehole and CALM sites are dipping towards a preferential direction indicates, that there is a different amount of incoming solar energy received by the monitored ground than compared to the average. Therefore, preferential slope orientation causes a bias in the overall representativeness of temperature monitoring and should be taken into account when using the data for global models.

4.5 The distribution of GTN-P sites within zones of projected temperature change

Climate models project temperature increases in the Arctic towards the end of the 21st Century that are larger than anywhere else on Earth (ACIA, 2004; Stocker et al., 2013). CMIP5 models show that for each degree of global temperature increase about 1.6×10^6 km^2 or ca. 1/4 of the present permafrost area is expected to start to disappear

(Koven et al., 2013) and boreal landscapes will most likely lose all present discontinuous permafrost zones by the end of the 21st Century (Slater and Lawrence, 2013). To assess the distribution quality of present permafrost temperature monitoring, we calculated the number of TSP and CALM sites per zone of projected temperature change for 15 different climate models. Differences of mean annual near surface temperature between 2070–2099 AD and 1970–2000 AD for representative concentration pathways (rcp's) 4.5 and 8.5 were taken into account for following models: ACCESS1-0, bcc-csm1-1, CanESM2, CCSM4, CNRM-CM5, CSIRO-MK3-6-0, GISS-E2-H, GISS-E2-H, GISS-E2-R, HadGEM2-ES, inmcm4, IPSL-CM5A-LR, MPI-ESM-LR, MRI-CGCM3 and NorESM1-M. Figure 11 shows that in rcp 4.5, an intermediate greenhouse gas emission scenario, most boreholes and CALM sites are located in relatively narrow zones of less extreme projected temperature change (ca. 3–6 °C for TSP and ca. 2–5 °C for CALM). The high-emission scenario rcp 8.5 projects a more extreme temperature increase for larger areas and more GTN-P monitoring sites are located in zones of up to a 10 °C potential temperature rise. A comparison of the applied models shows that, depending on the model uncertainties and variety of possible climate futures, the spatial distribution of projected temperature change varies from model to model. This is why increasing the number of soil temperature and active layer monitoring sites by filling main geographical gaps is critically important to constrain projections of climate change's impact on permafrost.

5 Conclusions

The GTN-P Database contains standardized and quality checked permafrost temperature and active layer thaw depth data from the Earth's permafrost regions: 1074 TSP boreholes and 274 CALM sites. The associated Data Management System provides automated visualization and data output formats developed for the needs of a high variety of users including climate modelers.

GTN-P metadata statistics can help to identify potential new monitoring sites. Vegetation types, soil organic carbon content and the slope orientation at boreholes and active layer depth monitoring sites show the existence of biases and hinder the representativeness of these sites at the global level. The distribution of GTN-P sites according to projected temperature change shows a high representation of areas with smaller expected temperature rise but a lower number of sites within arctic areas where climate models project extreme temperature rise.

We conclude that for gaining a representative global view on the thermal development of the Earth's permafrost landscapes, more permafrost monitoring sites must be established at key sites and entered into the GTN-P Database. These sites should be preferentially located in areas where monitoring is lacking, but also where soil organic carbon contents are high and projected temperature change is high. This paper offers a scientific basis and maps for planning future permafrost research monitoring sites, which could feed into existing planning efforts such as the Global Cryosphere Watch (GCW) Implementation Plan 2015 (http://globalcryospherewatch.org).

Author contributions. Leading author Boris K. Biskaborn (GTN-P scientific manager) was writing the manuscript, performed statistics (together with the Arctic Portal). Co-authors Jean-Pierre Lanckman developed the Data Management System of the GTN-P database; Hugues Lantuit (PAGE21 data management leader) was the initiator and main advisor for this study; Kirsten Elger contributed as former GTN-P manager to the database and in the data policy chapter of this article; Dmitry A. Streletskiy was the main advisor for CALM data; William L. Cable was the advisor for technical aspects of boreholes; Vladimir E. Romanovsky (director of GTN-P) was the main advisor for TSP data.

Acknowledgements. The main sponsor for the establishment of the GTN-P Database is the PAGE21 Project with financial support by the European Commission (FP7-ENV-2011, Grant Agreement no. 282700). The GTN-P Database was developed and is hosted at the Arctic Portal (Iceland) in collaboration with the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (Germany). The authors thank Eleanor Burke and Sarah Chatburn for providing materials and advice on climate models and NetCDF files. We further thank Kerstin Gillen, Almut Dreßler and Kira Rehfeld for their help with technical aspects and statistics.

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Table 1. TSP borehole and CALM active layer monitoring site distribution. Cell color darkens with increasing values within rows.

		Russia	USA/Alaska	Canada	Mongolia	Antarctica	China	Norway	Svalbard	Switzerland	Sweden	Greenland	Japan	Italy	Austria	Argentina	Kazakhstan	Iceland	Spain	Germany	Kyrgyztan	Finland
Boreholes per permafrost zone	Continuous	185	121	57	45	1	0	0	29	0	2	5	0	0	0	0	0	0	0	0	0	0
	Discontinuous	75	71	105	0	1	30	17	0	17	12	3	0	7	3	0	5	0	0	0	0	0
	Sporadic	2	3	29	9	0	7	16	0	0	0	1	0	0	0	0	0	0	0	0	0	1
	Isolated	9	0	3	37	0	0	0	0	12	5	1	7	2	5	0	0	1	0	2	0	0
	Other*	23	6	0	0	70	1	3	1	0	0	1	3	0	0	5	0	3	3	0	2	0
total BH/country		294	201	194	91	72	38	36	30	29	19	11	10	9	8	5	5	4	3	2	2	1
BH/km^2/country (x10^{-5})		1.7	2.1	2.0	5.8	0.6	0.3	11.2	47.6	72.3	4.3	0.5	2.7	3.0	9.5	0.2	0.2	3.9	0.6	0.6	1.0	0.3
total AL/country		61	67	31	46	9	11	1	7	2	1	3	0	0	0	0	3	0	0	0	0	0
AL/km^2/country (10^{-6})		3.6	7.1	3.1	29.4	5.8	1.2	3.1	111.0	48.2	2.2	1.4	0	0	0	0	1.1	0	0	0	0	0

*Other = glacier, no permafrost or unknown; BH = boreholes; AL = active layer sites

Table 2. Representation of Bioparameters within the borehole and active layer monitoring site distributions. Distribution of soil organic carbon contents in the top 200 cm from Northern Circumpolar Soil Carbon Database (Hugelius et al., 2013). Vegetation zones taken from the standardized GTN-P metadata.

	Bioparameter	TSP boreholes (%)	CALM grids (%)
Vegetation zone	Polar Desert	3.9	3.7
	Tundra	27.3	26.9
	Shrub Tundra	11.3	13.2
	Grassland	8.1	19.8
	Forest Tundra	11.9	12.4
	Coniferous Forest	11.4	5.8
	Deciduous Forest	2.5	1.7
	No Vegetation	11.6	2.9
	Other	11.9	13.6
Soil organic carbon	0 % or no value	18.4	10.7
	< 10 %	20.3	22.7
	10–25 %	34.3	37.6
	25–50 %	25.2	28.9
	> 50%	1.7	0.0

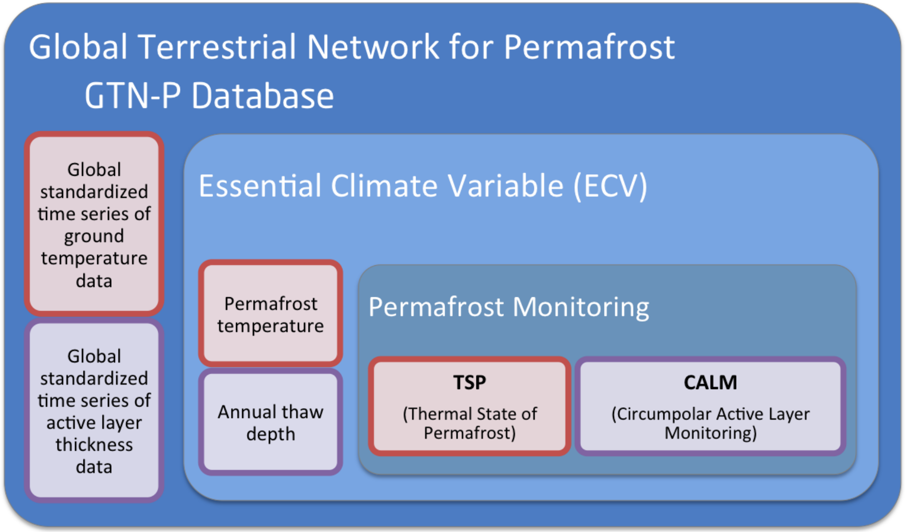

Figure 1. Framework within the Global Terrestrial Network for Permafrost defined by permafrost temperature and active layer thickness data from TSP and CALM programs, respectively.

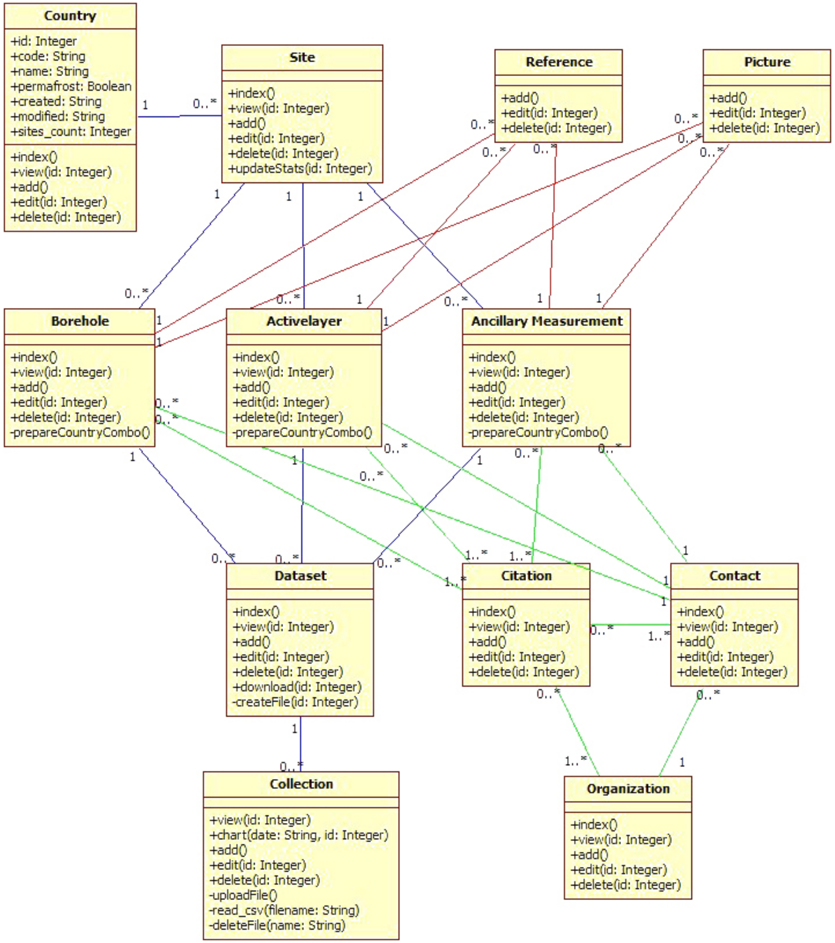

Figure 2. UML (Unified Modeling Language) diagram of the object-oriented GTN-P Data Management System and its classes, cardinalities and instances.

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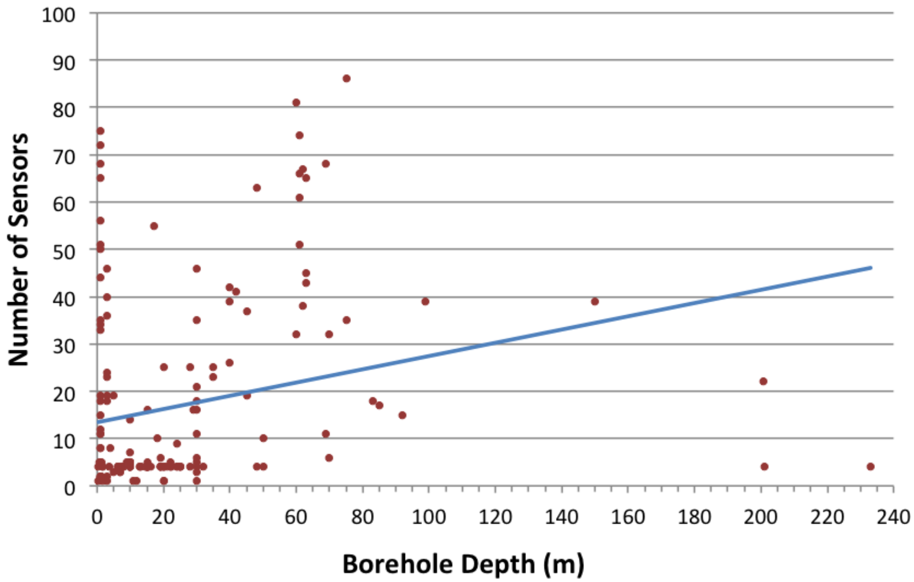

Figure 3. Number of temperature measurement sensors per borehole based on 180 datasets containing temperature time series data.

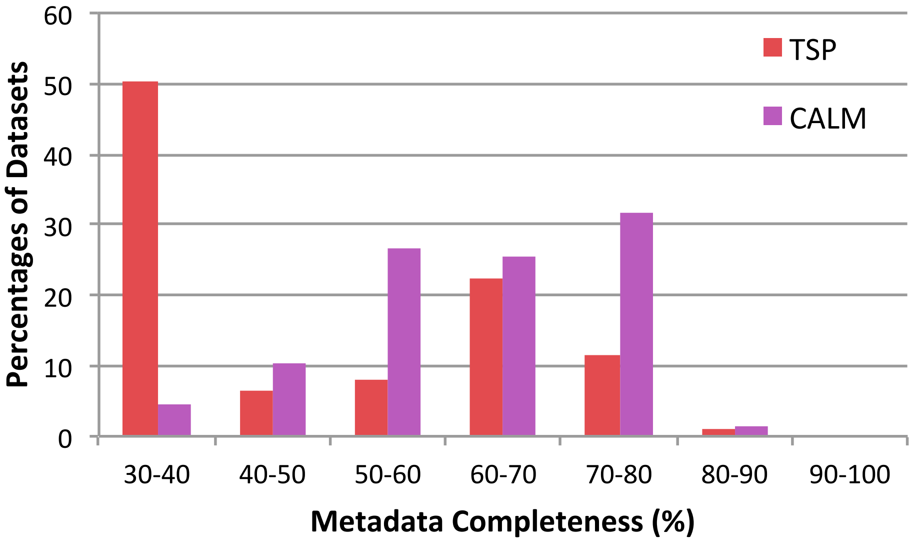

Figure 4. Metadata completeness in percent of filled-in metadata fields for TSP (1074 boreholes) and CALM (243 active layer monitoring sites).

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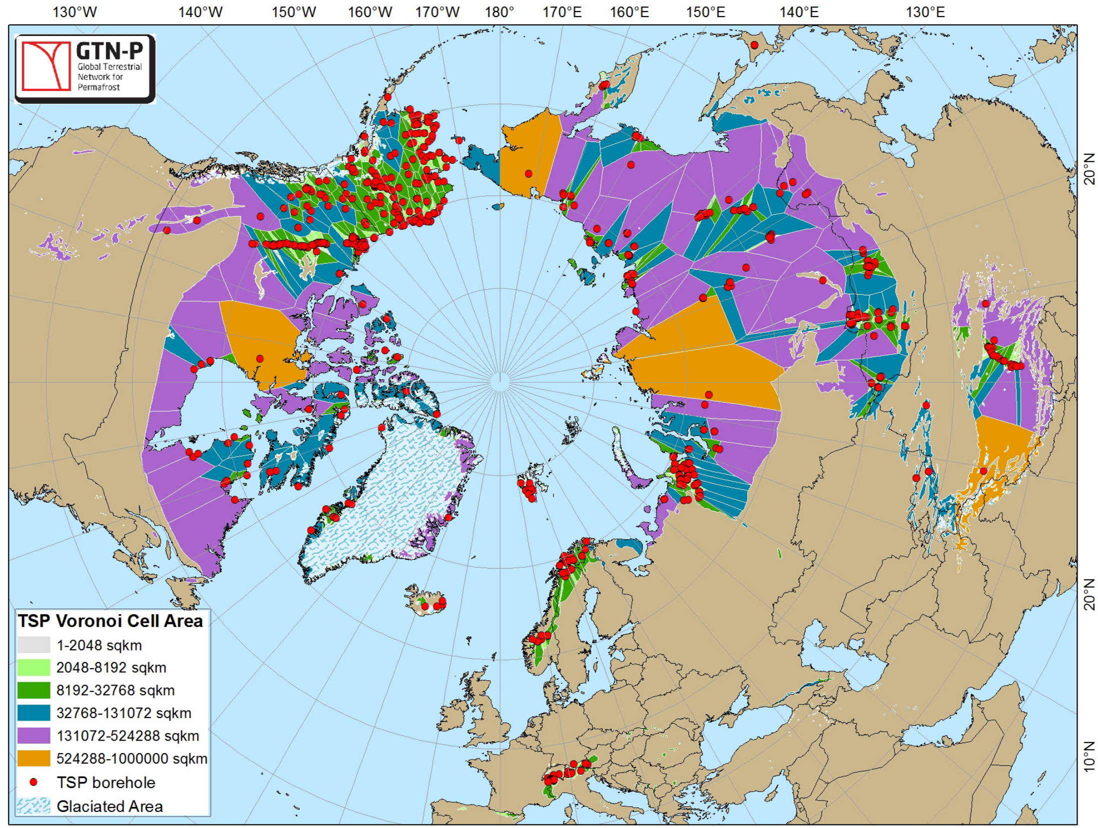

Figure 5. Voronoi Tessellation Analysis on the distribution of TSP boreholes in the Northern Hemisphere.

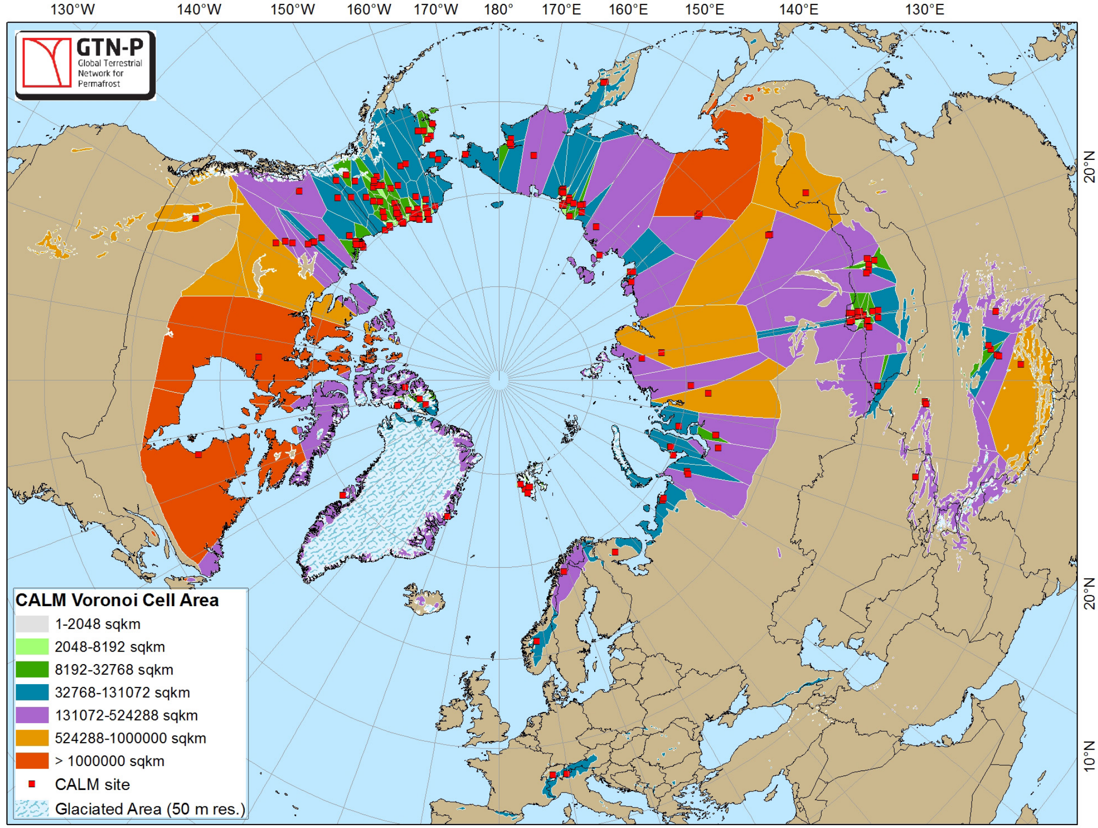

Figure 6. Voronoi Tessellation Analysis on the distribution of active layer monitoring sites (CALM) in the Northern Hemisphere.

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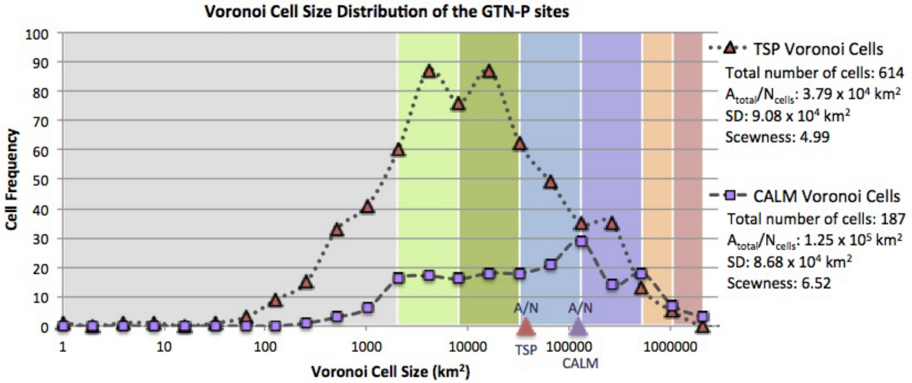

Figure 7. Voronoi cell size distribution according to the Voronoi Tessellation Analysis on the spatial distribution of boreholes (TSP) and active layer sites (CALM).

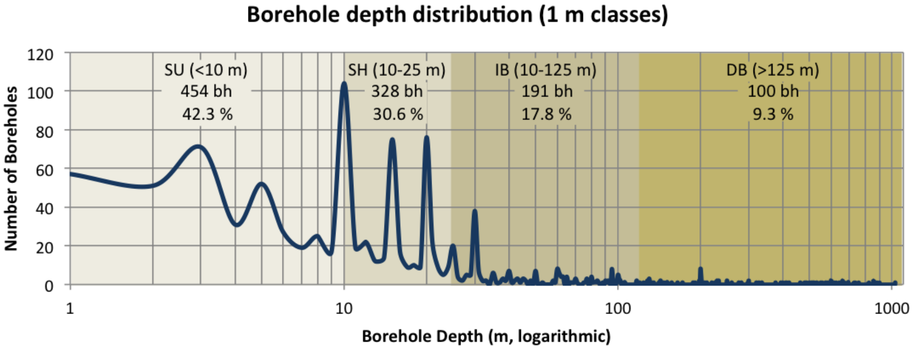

Figure 8. Total numbers of TSP boreholes (bh) and percentages of the GTN-P depth classes < 10 m SU Surface; 10–25 m SH Shallow; 25–125 m IB Intermediate borehole; > 125 m DB Deep borehole.

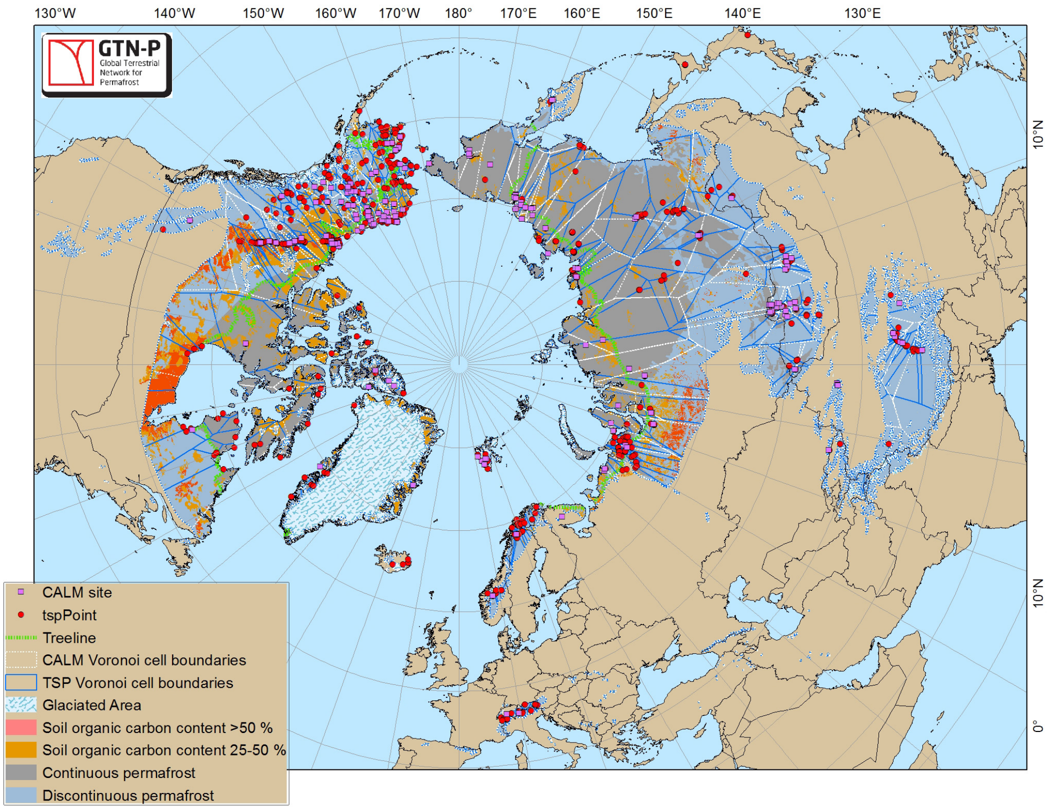

Figure 9. Boundaries of the TSP and CALM Voronoi cells indicate potential new sites for boreholes and active layer grids, respectively. The map also shows the spatial distribution of permafrost organic carbon content (Hugelius et al., 2013), the treeline (Brown et al., 1998) and the distribution of continuous and discontinuous (including sporadic permafrost and isolated patches) permafrost as well as glaciated areas.

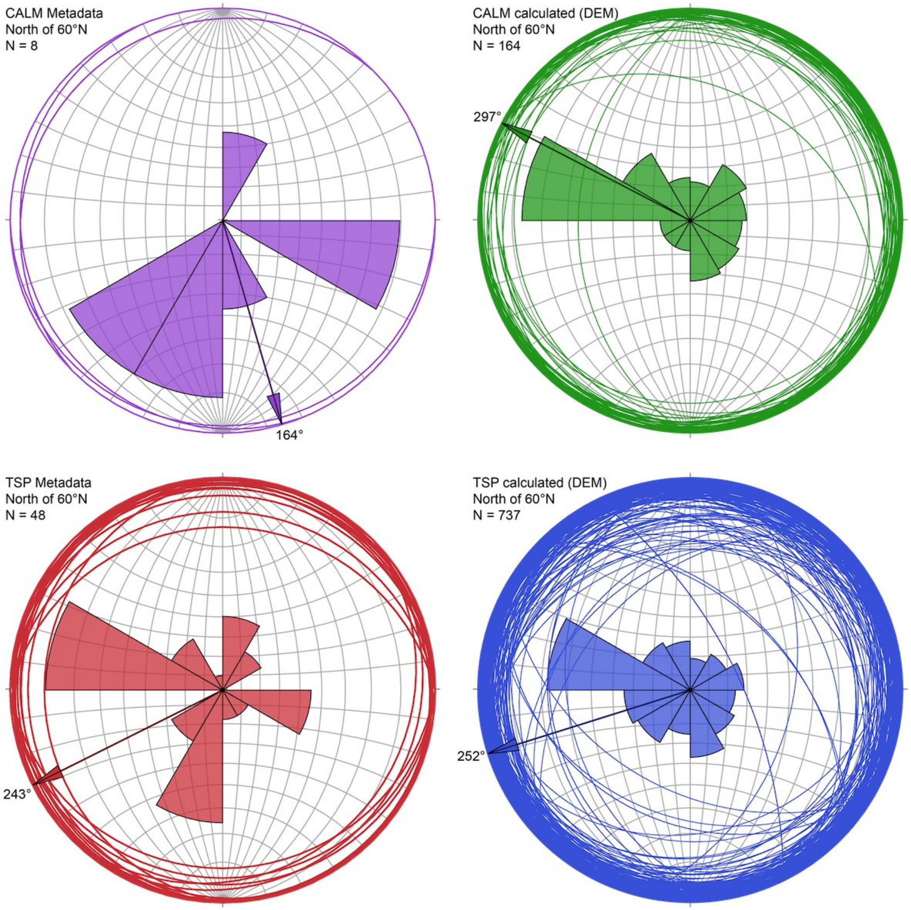

Figure 10. Terrains at TSP and CALM as spherical equal-angle projections in stereonets and the frequencies of slope aspects as a rose diagram with bin size = 30°. Circle lines represent sutures of planes (site terrain) and their orientation.

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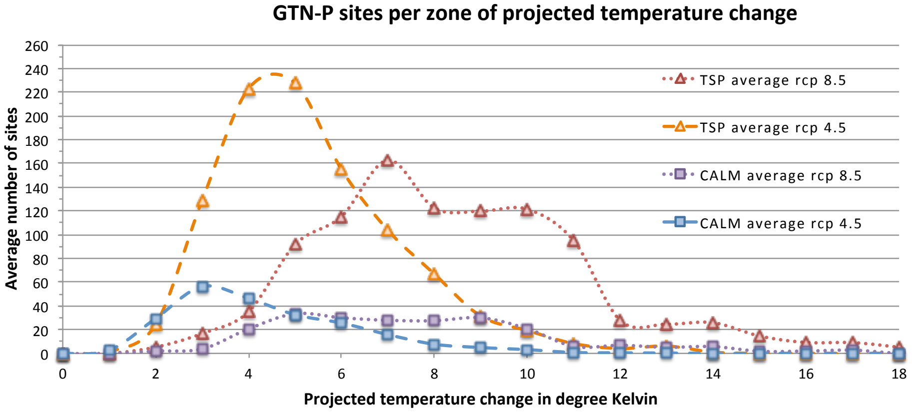

Figure 11. Average number of GTN-P sites within zones of projected temperature change calculated from 15 climate models: ACCESS1-0, bcc-csm1-1, CanESM2, CCSM4, CNRM-CM5, CSIRO-MK3-6-0, GISS-E2-H, GISS-E2-H, GISS-E2-R, HadGEM2-ES, inmcm4, IPSL-CM5A-LR, MPI-ESM-LR, MRI-CGCM3 and NorESM1-M. rcp: representative concentration pathway. KML-files for visualization of the TSP and CALM locations and the listed climate models in Google Earth is available at www.gtnp.org.