Quality assessment of permafrost thermal state and active layer thickness data in GTN-P

Boris K Biskaborn, Hugues Lantuit, Almut Dreßler
Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Potsdam, Germany
Jean-Pierre Lanckman, Halldór Jóhannsson
Arctic Portal, Akureyri, Iceland
Vladimir Romanovsky, William Cable
Geophysical Institute, University of Alaska Fairbanks, Fairbanks, USA
Dmitry Sergeev
Institute of Environmental Geoscience RAS, Russia
Gonçalo Vieira
CEG/Instituto de Geografia e Ordenamento do Território, Universidade de Lisboa, Lisbon, Portugal
Paolo Pogliotti
Environmental Protection Agency of Valle d'Aosta, Italy
Jeannette Nötzli
Department of Geography, University of Zurich, Zurich, Switzerland
Hanne H. Christiansen
Arctic Geology Department, University Centre in Svalbard, Longyearbyen, Norway

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ABSTRACT
The Global Terrestrial Network for Permafrost (GTN-P, gtnp.org) established the new 'dynamic' GTN-P Database (gtnpdatabase.org), which targets the Essential Climate Variable (ECV) permafrost, described by the thermal state of permafrost (TSP) and active layer thickness (ALT). This paper outlines the requirements for assessing the GTN-P data quality. Our aim is to conceive and discuss useful data quality indices as a basis for the 2nd official GTN-P National Correspondents Meeting in Quebec, September 2015. We describe the TSP and ALT data structures and the importance of precise metadata for the reliability of sound statements on the state and changes of permafrost. We define the most critical parameters related to quality assessment of TSP (borehole depth, number of sensors per depth, recording interval, sensor calibration) and ALT (grid structure, null values and exceeded maximum values, time consistency). We conceive and discuss a set of potential (to be reviewed at the GTN-P meeting) data quality indices by distinguishing between different borehole depths and spatial and temporal data dimensions of TSP and ALT datasets.

RÉSUMÉ
Le réseau terrestre global du pergélisol (GTN-P) a établi la nouvelle base de données dynamique (gtnpdatabase.org), qui cible les variables climatiques du pergélisol, décrites par l'état thermique du pergélisol (TSP) et l'épaisseur de la couche active (ALT). Cet article présente les exigences pour déterminer la qualité des données du GTN-P. L'objectif est de concevoir et discuter d'indices de qualité des données pour la 2ème rencontre des correspondants nationaux du GTN-P à Québec en septembre 2015. La structure des données du TSP et de l'ALT et l'importance de métadonnées précises pour la fiabilité de conclusions claires sur l'état et l'évolution du pergélisol sont décrites. Les paramètres les plus critiques reliés à la détermination de la qualité du TSP (profondeur du trou de forage, nombre de jauges par unité de profondeur, intervalle d'enregistrement, calibration des jauges) et de l'ALT (structure de la grille, valeurs nulles et valeurs maximales excédées, consistance des données de temps) sont définis. L'article propose une série d'indices de qualité des données potentiels en différenciant chaque profondeur de trou et dimension spatiale et temporelle des données du TSP et de l'ALT.

1 INTRODUCTION

The Global Terrestrial Network for Permafrost (GTN-P, gtnp.org) is the primary international programme concerned with organising permafrost observation parameters. GTN-P was developed in the 1990s, managed by the International Permafrost Association (IPA) under the Global Climate Observing System (GCOS) and the Global Terrestrial Observing Network (GTOS). The newly established 'dynamic' GTN-P Database contains time series describing the thermal state of permafrost (TSP) and the active layer thickness (ALT) from terrestrial panarctic, Antarctic and mountainous permafrost regions. GTN-P focuses on managing the collection, standardisation, storage and dissemination of data describing the Essential Climate Variable (ECV) permafrost by using up to date technical standards in an online Data Management System (gtnpdatabase.org). The observed parameters currently include permafrost temperature and active layer thickness

(Fig. 1). However, the collected data from international and national repositories and research groups reveal a broad spectrum of collection methodologies, processing steps and data formats. Therefore, the GTN-P Database management group aims to produce a consensus document that identifies (i) a strategy for data quality assessment, (ii) key parameters of permafrost variables, and (iii) an initiative to frame recommendations for international standard methods and protocol definitions. These efforts are important to integrate worldwide permafrost observations into international standards and to provide interfacing of new data possibilities to the global modeling community.

Here, we aim to outline the needs and possibilities of assessing the GTN-P data quality as a basis for discussions within the framework of the GEOQuébec 2015 Conference during the 2nd official GTN-P National Correspondents Meeting, in September 2015, Québec, Canada. Our specific goal is to conceive and discuss indices, which describe the quality of the TSP and ALT data numerically.

2 THE GTN-P DATA

The National Correspondents (NC) of GTN-P are the main suppliers of borehole data and Active Layer Thickness (ALT) data to the GTN-P Database. Many of the research groups are involved in the two international programmes TSP (Thermal State of Permafrost) and CALM (Circumpolar Active Layer Monitoring). To use GTN-P for assessing the quality of global permafrost observations, the methodologies within the different TSP and ALT data sources and the data transfer pathways to the GTN-P Data Management System (DMS) have to be considered (see also Cremonese et al., 2011). Biskaborn et al. (2015) described the GTN-P DMS in detail and applied statistics to the GTN-P metadata (GTN-P, 2015) to characterize the panarctic heterogeneity of the spatial sample distribution. In fall 2014, an IPA action group has formed with the aim to control and assure the GTN-P data quality.

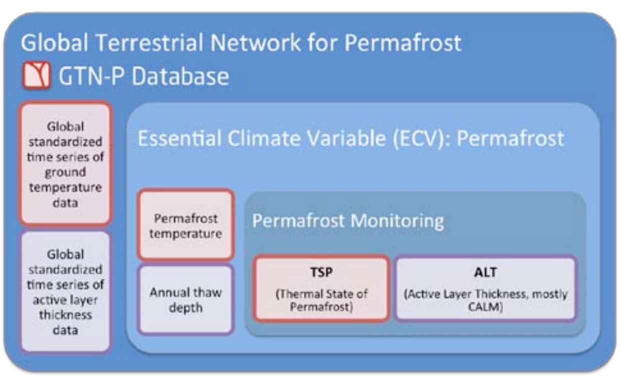

Figure 1. Essential Climate Variables in GTN-P, provided by TSP and ALT. Active Layer Thickness is mostly associated to CALM (Circumpolar Active Layer Monitoring).

2.1 TSP method and data structure

As described in the GTN-P Strategy and Implementation Plan 2012-2016 (GTN-P, 2012), TSP data are obtained by recording ground temperature from sensors permanently or temporarily lowered into a borehole, either manually with a portable temperature logging system or by data loggers. TSP data accuracy is normally about 0.1°C. However, the level of accuracy depends on the measurement equipment used and level of sensor calibration. Accordingly, different accuracy classes should be established for describing the accuracy of the temperature measurement for the boreholes.

At depths less than the depth of zero annual amplitude (ZAA, typically between 10 and 20 m), ground temperatures experience an annual cycle, which requires monthly but preferably higher sampling rates (depending on the depth of measurement) in order to compute yearly statistics with confidence. Between the ZAA and depths of about 50 m, annual temperature measurements are sufficient. At greater depths annual or less frequent measurements are acceptable. Within a borehole, the downwards spacing of sensors typically increases with depth, e.g. 1 m spacing in the shallow depths to 5-10 m spacing in the part of a borehole below about 20 m. Hence, the TSP possesses non-uniform data structures in the two dimensions space and time (Fig. 2).

Date/Offset (depth in m)	0.10	0.50	1.00	15.00
YYYY-MM-DD hh:mm	...	...	...	...
YYYY-MM-DD hh:mm	...	...	...	...
YYYY-MM-DD hh:mm	...	...	...	...
YYYY-MM-DD hh:mm	...	...	...	...
YYYY-MM-DD hh:mm	...	...	...	...

Figure 2. TSP data structure

2.2 ALT method and data structure

ALT is measured during the late thaw season (approximately from mid-August to mid-September in the Northern Hemisphere and around February in the Southern Hemisphere). The measurement is performed either by probing with a rod, with a frost/thaw tube (to account for subsidence) or ALT is calculated from soil temperature profiles, measured in shallow boreholes. Data accuracy of active layer thickness from mechanical probing and thaw tubes is typically about 1-2 cm (Nelson and Hinkel, 2003), but interpolated ALT accuracy from boreholes depends on vertical spacing of temperature measurements and interpolation method used (GTN-P, 2012).

Where possible (e.g. lowlands), gridded sampling designs or transects are used to acknowledge the spatial ALT variability. The grid sizes and transect lengths vary according to the local geomorphological, hydrological and vegetation setting. Following the CALM standard for grids, 121 nodes are evenly distributed within grids with side lengths between 10, 100, and 1000 m (Shiklomanov et al., 2008). ALT recorded in grids varies spatially and can also vary temporally. Hence, metadata about the interpolation method, the vertical thermistor spacing and the horizontal probe spacing are crucial parameters to assess data uncertainty.

Offset_Northing (m)	Offset_Easting (m)	YYYY-MM-DD	YYYY-MM-DD	YYYY-MM-DD
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...

Figure 3. ALT (CALM) data structure

2.3 The importance of TSP and ALT metadata

Precise metadata based on existing ISO geospatial standards, e.g. coordinates and additional observations on the surrounding environment are a basic requirement to assess and sustain the data quality for comparative studies. To illustrate, metadata can also summarize information about potential disturbances nearby measurement sites which influences temperature values.

The data management work package of the EU project PAGE21 standardised and imported more than 1000 datasets from the Arctic from different repositories into the GTN-P Database. Available metadata information has been transferred to the Data Management System following the ISO19115 documentation by developing a metadata framework suitable for permafrost monitoring sites. This process and the metadata statistics performed subsequently (Biskaborn et al., 2015) showed that without sufficient metadata quality, geo-data are of very limited usage for a number of geospatial analyses and thus do not allow reliable interpretation. A simple example is given by the low resolution of a number of CALM grid references and TSP borehole coordinates. 374 datasets (of about 1350) had coordinates in decimal degree with a precision below 4 decimal places of either the latitude or the longitude or both, which, in extreme cases, resulted in terrestrial borehole coordinates plotted erroneously a few hundred meters to a few kilometers offshore. Regarding the small scale and generally high spatial and temporal variability of environmental features, precise metadata are obligatory for a reliable application of the data in geoscience. Also, the time format of the measurements must be indicated in a way which can be unmistakably identified by a third person. The format in the GTN-P templates is YYYY-MM-DD hh:mm (Fig. 2 and 3).

The data upload to the GTN-P Database involves a number of obligatory and mandatory fields for specific metadata, when possible organised as drop down menus to assure standardisation. Mandatory metadata are as follows:

- TSP borehole or CALM grid name
- coordinates
- time zone
- site name
- borehole depth
- vegetation type
- responsible person/citation

The most important additional metadata fields are: former data code (TSP / CALM code), permafrost zone, borehole drilling method, measurement method, environmental setting (landform and overall geomorphological setting, lithology, hydrology, specific vegetation, slope and aspect), accessibility, disturbances, and other descriptions.

3 GTN-P DATA QUALITY - TSP

3.1 Defining key parameters to describe the TSP data quality

The main variables to describe the thermal state of permafrost in boreholes are temperature, time and depth and it seems feasible to handle these three entities. The complexity, however, increases exponentially with the preferential claim for standardisation. To be able to compare data from different boreholes the following parameters must be taken into account:

- borehole depth (or depth of deepest sensor)
- number of sensors per depth
- number of measurements per unit time
- length and continuity of the time series
- quality and frequency of sensor calibration and standard deviation

Facts about these parameters, which are relevant for assessing the quality of a potential composite dataset, are the following:

- The borehole depths vary according to the opportunities and goals of the drilling projects, which aimed normally for even depths, e.g. 3, 5, 10, 20 and 30 meters. The mean depth of all boreholes in the GTN-P Database is 53 m.
- The number of sensors per borehole has no linear consistency between number of sensors and the borehole depth (Fig. 4). Also, due to high geomorphological surface and subsurface dynamics, the relative vertical position of probes can change and bias the depth indications of old boreholes in sensitive areas.
- The number of measurements per time vary not only from borehole to borehole, but also between time series from the same borehole. Within the boreholes, the deviation of the numbers of temperature recordings per time unit ranges from 0 to 57 measurements (Biskaborn et al., 2015).
- Time series of temperature data from boreholes may reveal gaps which do not allow the accurate and continued calculation of mean annual ground temperatures. The length and consistency of the time series, however, are among the most important quality factors needed for assessing the thermal state of permafrost. The possibilities and limitations for interpolations across data gaps in borehole temperatures also depend on the length and the time of the gap and the depth of measurement (below or above the ZAA). Long-time interruptions in measurements cause the derivation of number of data sets from the absolute number of boreholes (Fig. 4).
- Sensors have sometimes been calibrated using different methods during different national and international projects and the standard deviations of the measurements vary. Additionally, errors caused by technical problems, e.g. sensor drift, water impact, noise resulting from electronics can have a major impact on the data quality.

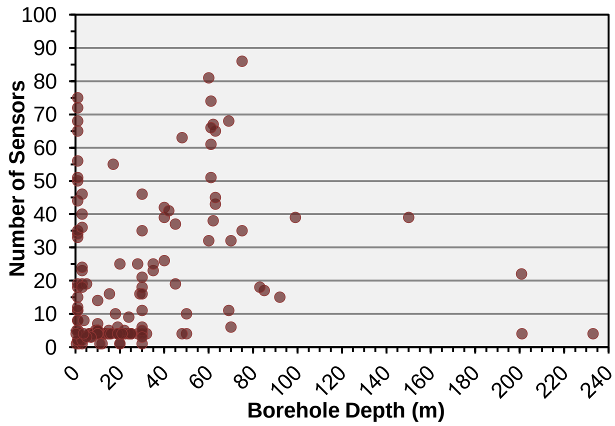

Figure 4. Number of sensors per borehole depth of 179 data sets of 158 PAGE21 boreholes

3.2 Quality concerns for ground temperature statistics

To assess the thermal conditions of permafrost, commonly the mean annual ground temperature (MAGT) and the depth of ZAA are calculated from the original data. Above the ZAA, the annual temperature fluctuations are visible in the time series and, if the sample distribution through time is uneven, it can bias the mean values desired to describe the long-term permafrost thermal development. The ZAA generally occurs within 20 m of the ground surface, varying according to the thermo-physical properties of the subsurface material, overlying vegetation, and topography (Romanovsky et al., 2010) as well as so called "thermal diffusivity" or sudden changes of the geothermal heat flux (French, 2007).

4 GTN-P DATA QUALITY - ALT

4.1 Defining key parameters to describe the CALM data quality

Active layer thickness information is present as point, line or grid data. The complex nature of grid metadata caused inconsistencies in the structure and format of the primary data files related to the following parameters:

- grid structure
- null values and exceeded maximum values
- time consistency
- length of time series

Standardised grid data require a consistent reference point, which is the lower left point of the GTN-P template grid for CALM data. Every other point requires the offset from the reference point (northing and easting).

In the dataset, it is crucial, to distinguish between null values (no data exist, indicated by -999) and exceeded maximum measurement capacity (EMMC). EMMC appears when, for example, the probe used for measurement is not long enough to reach the permafrost (indicated by -888).

The remoteness of the ALT sites, the expensive logistics and thus funding related to fieldwork potentially lead to inconsistent interannual recording time. A difference of a few weeks can cause significant deviation from the end-of-season maximum of the annual thaw depths. Hence, there is a potential bias in the active layer thickness data directly related to the methodology and this bias will be always towards a thinner ALT.

5 PRELIMINARY RESULTS AND DISCUSSION

In this section, we provide suggestions how to address the GTN-P data quality assessment on a numerical basis. The general data control concept of GTN-P is linked to the involvement of the work of national correspondents which are responsible for the quality check. Permafrost scientists can make use of the automated data visualisation in the GTN-P database to verify the correct data format and consistency, e.g. to detect outliers.
In this stage it is not a final result, but a recommendation as an initial outcome of the discussions within the IPA action group on GTN-P data quality and other authors of this paper and serves as a starting point for further discussions.

5.1 Strategies for assessing the TSP data quality

The first approach refers to the spatial resolution of temperature measurements. Hence, an index xs [1] describing the sensor spacing in a borehole as numbers of sensors s per borehole depth bd:

$$xs = \frac{s}{bd} \qquad [1]$$

Equation [1] would be biased, because xs decreases with increasing borehole depth. In general, a high index xs describes a high definition by sensors. With increasing depth below the ZAA the number of sensors usually decreases. However, boreholes have been sorted into depth classes (<1
0;10-25;25-125;>125m) by GTN-P (Burgess et al., 2000; Fig. 5). Distinguishing between different depth categories can enable the assessment of a borehole's value for active layer monitoring, investigating the surface seasonal temperature variation above the depth of ZAA and the value at the ZAA, and determining the permafrost base. Next to the borehole depth classification within GTN-P (Fig. 5), the specific depth of ZAA can require another categorization of depth classes.

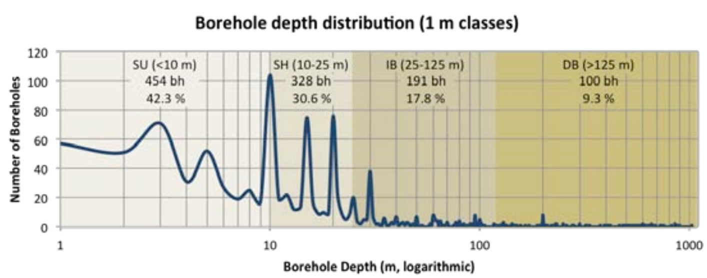

Figure 5. TSP borehole depth distribution in GTN-P

If the GTN-P depth classes are modified to the actual borehole depth distribution (Fig. 4) and the needs of the data quality assessment and permafrost observation aims, a borehole could receive a number of indices to describe its observing quality. These indices could be applied in the database search-function in order to list all boreholes fulfilling the individual scientific quality criteria.

$$xs_{y-z} = \frac{s_{y-zm}}{bd_{y-zm}} \qquad [2]$$

Equation [2] is related to borehole sections between an upper borehole depth y and a lower borehole depth z. We applied two possible scenarios with simplified example to show how this equation could be implemented:

Scenario 1 "dynamic indices"

The first "<2 m index $xs_{<2}$" is based on the total borehole depth if the borehole is shallower than 2 m. Rule applies until 2 m are reached.

The second "2-25 m index xs_{2-25}" is based on the total depth if the borehole is shallower than 25 m. Rule applies until 25 m are reached.

The third ">25 m index $xs_{>25}$" is based on the total borehole depth if the borehole depth exceeds 25 m.

Example 1.1:

Borehole depth 25 m, sensors at 0, 0.5, 1, 1.5, 2, 3, 4, 5, 10, 15, 20, 25 m

$xs_{<2}$=5/2=2.5
xs_{2-25}=8/(25-2)=0.32

Example 1.2:

Borehole depth 15 m, sensors at 0, 0.5, 1, 1.5, 2, 3, 4, 5, 10, 15 m

$xs_{<2}$=5/2=2.5
xs_{2-15}=6/(15-2)=0.46

Conclusion for scenario 1: Indices vary, although the over-all vertical measurement resolution is the same until 15 m. A comparison of these indices shows that the borehole depths as well as the classification of depths are crucial information. It would not be easy to apply indices as filters to the database, because it would result in a very high "dynamic" number of indices.

Scenario 2 "high number of controlled indices, following the GTN-P borehole depth distribution pattern"

Example 2.1:

Borehole depth 25 m, sensors at 0, 0.5, 1, 1.5, 2, 3, 4, 5, 10, 15, 20, 25 m

xs_{0-2}=5/2=2.5
xs_{2-5}=4/3=1.3
xs_{2-10}=2/5=0.4
xs_{10-15}=2/5=0.4
xs_{15-20}=2/5=0.4
xs_{20-30}=2/10= 0.2*
$xs_{>30}$= N.A.
*does not reach lower index boundary

Example 2.2:

Borehole depth 15 m, sensors at 0, 0.5, 1, 1.5, 2, 3, 4, 5, 10, 15 m

xs_{0-2}=5/2=2.5
xs_{2-5}=4/3=1.3
xs_{2-10}=2/5=0.4
xs_{10-15}=2/5=0.4
xs_{15-20}= N.A.
xs_{20-30}= N.A.
$xs_{>30}$= N.A.

Example 2.3:

Borehole depth 5 m, sensors at 0, 0.2, 0.4, 0.6, 0.8, 1, 1.3, 1.6, 2, 3, 5 m

xs_{0-2}=9/2=4.5
xs_{2-5}=3/3=1.0
xs_{2-10}= N.A.
xs_{10-15}= N.A.
xs_{15-20}= N.A.
xs_{20-30}= N.A.
$xs_{>30}$= N.A.

Conclusion for scenario 2: Indices are more stable and the over-all resolution is the same. However, there is still a bias for boreholes, which total depths do not match the index boundaries and the high number of indices can cause undesirable complexity in the data quality assessment in the database search function.

The presented indices refer to spatial resolution. The specific number and distribution of sensors depends on the local setting of the site and the methodological approach of the permafrost researcher and hence cannot be included in a quantitative approach.

The above shown scenarios and potentially more possibilities will be further discussed during the 2nd GTN-P NC Workshop.

The total length of the data series is described by the simple index Δd_{TSP}:

$$\Delta d_{TSP} = ((latest\ year) - (earliest\ year)) \qquad [3]$$

Δd_{TSP} is valid for data series which provide values for several years. Incomplete years as well as lacking values within series can not be identified without a detailed study of data sets.

The temporal resolution xt can be calculated from the number of measurements nM in the most recent or any other completed year a^* for each of the above categories to acknowledge the different measurement purposes [4]:

$$xt_{y-z} = \frac{nM_{y-zm}}{a^*} \qquad [a^* = 365\ days] \qquad [4]$$

The interannual consistency ta of the time series can be described by calculating the average number of time units containing measurements [5]. Given the different temporal needs of the monitoring aims, these calculations should also adapt to the different borehole depth sections, i.e. by applying weekly, monthly and yearly resolution:

$$ta_{y-z} = \frac{nt_{My-zm}}{nt_{total}} \quad [5]$$

nt_{total} is the number of time units between the start and the end of the time series. nt_{My-zm} is the number of time units, which have measurements from y to z m in the borehole. If a week, month or year has no measurement, this time unit is not counted. According to the desired temporal resolution, which is (in priority) allowed to decrease with increasing borehole depth, the time units nt could be calculated as weeks, months or years, depending to the different borehole sections.

ta_{0-2} in days,
ta_{2-5} in weeks,
ta_{2-10} in weeks,
ta_{10-15} in months,
ta_{15-20} in months,
ta_{20-30} in months,
$ta_{>30}$ in years.

As a matter of course, the actual frequency of measurements depends on several requirements and conditions like the soil substrate and its assumed variation in temperature. The suggested time units base on average soil substrates and help quantifying the data quality and especially the time consistency.

The complex nature of observing permafrost dynamics also requires a quality assessment beyond the numerical possibilities. Experienced permafrost researchers were nominated as National Correspondents by GTN-P. Their responsibility is to evaluate the borehole data of their country and provide recommendations. How to address this strategically will be an important part of the discussions during the upcoming 2nd GTN-P NC workshop.

Considering the technical errors related to the measurements (see descriptions above), we suggest that a set of “accuracy classes” should additionally be established for describing the accuracy of the temperature measurement for the boreholes. Moreover, values for describing the measurement accuracy should be part of the mandatory GTN-P metadata. The metadata completeness, outlined by Biskaborn et al. (2015) in percentage of filled-in metadata fields, serves as a quality index describing the available information from the observation site.

5.2 Strategies for assessing the ALT data quality

ALT grid data can receive a simple spatial density index xA [6] by calculating the number of measurements nM (usually 121) per area A (in m^2).

$$xA = \frac{nM}{A} \quad [6]$$

Due to the variation of grid size, the index xA decreases with increasing grid area.

The time consistency of ALT time series gathered by the frost/thaw tube method could be expressed by the total number of measured years Δd_{ALT} and the interannual difference of days between the latest and the first measurement, performed by t_{ALT}:

$$\Delta d_{ALT} = ((latest\ year) - (earliest\ year)) \quad [7]$$

$$t_{ALT} = ((latest\ day) - (earliest\ day)) \quad [8]$$

These indices describe the total length of data series as well as the duration of measurements per year. They neither consider the frequency nor interruptions in ALT time series. But these indices are useful criteria for data search in the database. According to literature research, the quality assessment of permafrost data within GTN-P database is the first approach of a quality analysis of these data types. Further description of the data and time consistency of ALT measurements will be done within the IPA action group during the GTN-P workshop associated to GEOQuebec2015.

CONCLUSIONS

Initiated and managed by the EU project PAGE21, permafrost data could, for the first time, be organized and standardised in a dynamic online database open source technologies. The GTN-P Secretariat established an IPA action group addressing quality control and assurance of the active layer thickness (ALT) and permafrost temperature (TSP) essential climate variables within the GTN-P Database. In this paper, we suggest a set of strategies and indices for describing the scientific value and quality of TSP and ALT data, which have to be discussed with the National Correspondents at the 2nd GTN-P NC Workshop, and presented subsequently at the 7th Canadian Permafrost Conference at GEOQuebec2015.

The criteria for assessing the quality of a dataset depend on the intended use and objectives of the analysis. In such sense, the value of e.g. borehole depth, density of data in time and depth can be questionable. However, the length and continuity of the time-series, the absolute accuracy of the sensors, as well as the completeness and accuracy of metadata are quality criteria independent from the intended use.

During the 2nd GTN-P NC Workshop it will therefore be discussed what could be the most important use of the dataset from GTN-P. The GTN-P governing body will consequently evaluate weather or not all the identified quality-indices are needed – and if other key variables and indices are needed.

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