GTN-P
Global Terrestrial Network for Permafrost

Measurement Recommendations and Guidelines

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This is an interim document. It will be substituted by the Permafrost Best Practices that will be published as part of the Update of the World Meteorological Organization Guide No. 8. Please go to https://community.wmo.int/activity-areas/imop/wmo-no_8 for more information about the status of the guide.

Definitions

The definitions applied by Global Terrestrial Network for Permafrost (GTN-P) are in alignment with the WMO Permafrost Best Practices (WMO, in prep.) and the GCOS Permafrost ECV definitions.

Permafrost: Subsurface material that remains continuously at or below 0°C throughout at least two consecutive years.

Active Layer: The surface layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.

Rock Glacier: Debris landform generated by the former or current creep of frozen ground, detectable in the landscape with the following morphologies: front lateral margins and optionally ridge-and-furrow surface topography.

ECV Permafrost Products and Units of Measure

To comply with the WMO definitions and best practices, we have changed the variable name from Thermal State of Permafrost (TSP) to Permafrost Temperature (PT).

Permafrost Temperature (PT): Ground temperatures measured at specified depths (°C).

Active Layer Thickness (ALT): Thickness of seasonally thawed ground measured in centimetres (cm).

Rock Glacier Velocity (RGV): Surface velocity of a single rock glacier unit in metres per year.

Measurement Recommendations and Guidelines

Permafrost has been identified by GCOS as an Essential Climate Variable (ECV) (GCOS, 2016). Requirements for ECV's are defined for each ECV product (Permafrost temperature PT, Active Layer Thickness ALT, and Rock Glacier Velocity RGV) on individual ECV requirement sheets. These were produced and recently revised by GCOS/TOPC and will be released with the next GCOS Implementation Plan. Requirements are defined in terms of horizontal, vertical and temporal spacing, accuracy, stability and timeliness, with three levels (1. threshold = minimum requirement for consideration; 2. threshold = improved values allowing additional interpretation; and 3. goal = ideal data quality). GTN-P seeks to reach these requirements, and to promote their implementation by all contributors to the network. Methods, protocols and standards for permafrost field measurements in the context of long-term climate-related observation are being elaborated by the GCW Permafrost Best Practice Task Team, and will be published in the updated WMO Guide No. 8.

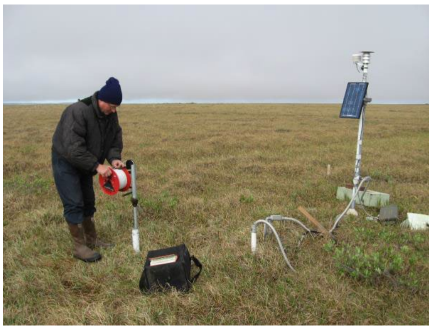
Since these documents are still being compiled and edited and are not yet publicly available, the GTN-P website provides a synthetic overview on methods and protocols. It is largely based on the assessment of the status of the original development of the standards for the Terrestrial ECV (T7) Permafrost (Smith and Brown, 2009). It provides a summary of existing and most common standards for the two ECV products Permafrost Temperature (PT) and Active Layer Thickness (ALT).

The definitions and best practice recommendations for the new third product Rock Glacier Velocity (RGV) are currently being developed by the IPA Action Group *Rock Glacier Inventories and Kinematics*. All relevant information about RGV is accessible and frequently updated on the RGV Action Group website (RGV Action Group, 2021).

Permafrost Temperature (PT)

Permafrost Temperature defines the thermal state of permafrost and is typically measured in boreholes. The typical depth of boreholes varies from less than 10 m to more than 100 m. It is advisable to drill permafrost boreholes with air flushing to have least disturbance of the thermal regime and ground ice conditions, and to install a casing and a covering structure at the surface to protect the instruments and to limit air convection (e.g., Noetzli et al. 2021). Temperature measurements in boreholes may be recorded manually with a portable temperature logging system or continuously or intermittently by fixed-installed data loggers. The accuracy and resolution of the sensors and measurements varies but it is advisable to aim for an accuracy of ±0.1°C or better to detect changes in permafrost temperature. If possible, thermistor strings should be periodically retrieved from the boreholes for recalibration and essential maintenance.

At shallower depths, generally less than 15 m, ground temperatures experience an annual temperature cycle and it is desirable to have several measurements throughout the year, depending on the depth and corresponding temperature variability (e.g. Noetzli et al. 2021). At depths below the penetration of the annual temperature wave (i.e., the depth of zero annual amplitude, ZAA), and up to depths of about 50 m, annual temperature measurements are sufficient to assess conductive processes. At greater depths where temperatures change slowly, biennial or less frequent (5–10 years) measurements are sufficient to capture long-term changes in permafrost temperature. With increasing permafrost degradation, more advective processes may become relevant, which cannot be captured with measurements of low temporal resolution. In light of increasing mean annual temperatures at the majority of GTN-P boreholes (Biskaborn et al., 2019) it is recommended to increase the frequency of permafrost temperature measurements (if possible) in case considerable warming is observed.



Data loggers may be utilized for repetitive daily to hourly measurements. They provide a continuous record of ground temperatures without increasing the number of site visits and with respective installation can be accessed remotely for (near) real-time data. If remote access is not available, periodic visits are required to acquire data from loggers. Spacing of sensors on cables (or the spacing of measurements if single sensor used) generally increases with depth. For example, in the uppermost 5 to 10 m, sensor spacing of 0.5 to 1 m can adequately define the shallow thermal regime while spacing may increase to 5 to 10 m or more at depths below the ZAA. Within the EU Project PACE a standard for the sensor spacing for a 100 m borehole was defined (Harris et al. 2001): 0.2, 0.4, 0.8, 1.2, 1.6, 2, 2.5, 3, 3.5, 4, 5, 7, 9, 10, 11, 13, 15, 20, 25, 30, 40, 50, 60, 70, 80, 85, 90, 95, 97.5 and 100 m. Adaptation to site specific characteristics may however be required when knowledge on the subsurface characteristics is available. In coarse blocky surfaces, for example in a rock glacier, measurements above ca. 1 m depth may be difficult to interpret due to the often unclear definition of the actual surface (Noetzli et al. 2021). Where recalibration is prevented due to blocked sensor cables (e.g., due to terrain deformation), duplicate measurements at key depths help to assess the long-term quality of the measurements (Noetzli et al. 2021).

The minimum desirable sensor spacing for continuous measurements using data loggers (e.g., measurements every 4 to 6 hours) for boreholes less than 15 m deep are: 3, 5, 10 meters and at the bottom of the borehole. For boreholes deeper than 15 m: 5, 10, 15, 20 meters and at the maximum depth of the borehole. In the absence of data loggers, the maximum and minimum annual temperature at each depth above the level of zero amplitude can be utilized to characterize the ground thermal regime. Other parameters derived from the permafrost temperature measurements are the mean ground temperature at each depth, the depth of the zero annual amplitude (ZAA) or the active layer thickness (see below). Where temperatures are available at deeper depths, the base of the permafrost may also be estimated. This may be done through interpolation between sensors if temperatures are measured below the base of permafrost, or by extrapolation. For additional detailed discussion of high precision temperature measurements, the reader is directed to Clow (2008). In mountain permafrost, the distortion of the profile due to complex topography commonly requires additional modelling below the deepest sensor to determine the permafrost base (Noetzli and Gruber 2009).

Ground Temperature Profiles

Ground and air temperature are recorded as basic information at many sites, especially with the increasing availability of inexpensive, reliable temperature data loggers. Temperature sensors (usually thermistors) are inserted into the active layer and upper permafrost as a vertical array. Several installations currently use an array of thermistors embedded in a small-diameter acrylic cylinder and connected to a high-capacity data logger. Ground temperature should be recorded at approximately one - to three-hour intervals, measured at a sensor interval of 10–20 cm, and on a seasonal basis to determine the maximum thaw penetration or additionally on an annual basis to establish mean annual ground temperatures. Freeze-thaw processes periodically act to "jack" the instrument vertically out of its original position, which may result in biases over the long-term periods (Urban and Clow, 2021).

In regions where there is no significant freezing point depression and the annual depth of thawing is corresponding to the 0°C isotherm, temperature records from a vertical array of sensors can be used to determine active-layer thickness at a point location, e.g. in boreholes. For mountain areas, where permafrost is typically found in debris and coarse blocky areas or in bedrock, this is the only applicable method to determine ALT (cf. Noetzli et al. 2021). The thickness of the active layer is linearly interpolated using the highest temperatures recorded at the uppermost thermistor in the permafrost and the lowermost thermistor in the active layer. For this reason, the probe spacing, data collection interval, and interpolation method are crucial parameters in assessing the accuracy and precision of the estimate (Riseborough, 2008). The uncertainty of the modern ground temperature measurements can be as low as 0.02–0.05°C, so probe spacing becomes more critical in the interpolation process.

Active Layer Thickness (ALT)

At most active layer monitoring sites, the maximum thaw depth (thickness of the active layer) is determined. However, the dynamics of the active layer, i.e., its seasonal progression, may also be monitored at sites of intensive investigations for process understanding. Several traditional methods reviewed by Nelson and Hinkel (2003) are used to determine the seasonal and long-term changes in thickness of the active layer: mechanical probing once seasonally, frost (or thaw) tubes and interpolation of ground temperatures obtained by data loggers. The CALM program's flexibility with respect to sampling design has led to significant insights into active-layer dynamics through formal field experiments (e.g., Nelson et al., 1999; Mazhitova and Kaverin, 2007). The [CALM website](https://www2.gwu.edu/~calm/) provides further information and a sampling protocol (https://www2.gwu.edu/~calm/).

Mechanical Probing

The minimum observation required is a late season measurement of the thickness of the active layer. However, additional observations on soil, vegetation and climate parameters are encouraged and can be entered as metadata in the GTN-P Data Management System. The desired time of probing varies with location, ranging from mid-August to mid-September in the Northern Hemisphere, and early February to late March in the Southern Hemisphere, when thaw depths are near their end-of-season maximum. Probing utilizes a graduated metal (e.g., stainless steel) rod, with a tapered point and handle, typically 1 cm in diameter and about 2 m long. Longer probes may be used where active layers are thicker, although difficulties may arise when probing to greater depth. The probe rod is inserted into the ground to the point of resistance which is associated with a distinctive sound and contact that is apparent when frozen ground is encountered. All measurements are made relative to the surface; in standing water, both thaw depth and water depth are recorded. Typically, two to three measurements are made at each location and the average is reported. If a standard spacing is maintained between the two sampling points, probing is performed within one meter of each other.

A gridded sampling design or transect allows for analyses of intra- and inter-site spatial variability (Nelson et al., 1998, 1999; Burgess et al., 2000). The size of the plots or grid and length of the transects vary depending on site geometry and design; grids range between 10, 100, and 1000 m on a side, with nodes distributed evenly at 1, 10, or 100 m spacing, respectively. The method accuracy is within 1 cm. In regions underlain by ice-rich permafrost, thaw settlement may lead to the underestimation of the progression of thaw and the loss of permafrost (Shiklomanov et al., 2013; Streletskiy et al., 2016).

Frost/Thaw Tubes

When read periodically, frost tubes provide information about seasonal progression of thaw and/or maximum seasonal thaw. The exact vertical position of a single frost tube should be determined at the end of the first summer of active layer measurements by selecting a point representative of the mean active-layer depth for the entire grid. Thaw/frost tubes are devices extending from above the ground surface through the active layer into the underlying permafrost. They have been used extensively in Canada. Construction materials, design specifications, and installation instructions are available for several variants of the basic principle (Rickard and Brown, 1972; Mackay, 1973; Nixon, 2000). A rigid outer tube is inserted into permafrost, and serves as a vertically stable reference; an inner, flexible tube is filled with water or sand containing dye, or beads with water. The approximate position of the thawed active layer is indicated by the presence of ice in the tube, or by the boundary of the colourless sand that corresponds to the adjacent frozen soil. Each summer the thaw depth, surface level, and maximum heave or subsidence is measured relative to the immobile outer tube. These measurements are used to derive two values for the preceding summer: (1) the maximum thaw penetration, independent of the ground surface and corrected to a standard height above the ground established during installation (i.e., a fixed datum); and (2) the active layer thickness, assumed to coincide with maximum surface subsidence. With modifications, the accuracy of the measurements is about 2 cm.

Metadata and Ancillary Data

Metadata is additional descriptive information (data) about data and according to the GCOS Monitoring Principles should be documented and treated with the same care as the data themselves (GCOS, after COP, 2003). It may contain for example important descriptive information about the measurements and instruments used and their changes, or about the sites, or the circumstances of the measurements. Such information is important for data quality control and to contextualize the measurements for data users. Additional data collected at monitoring sites may help to support the interpretation of active layer thickness and permafrost temperature data and to characterize the relationship between permafrost conditions and climate or local factors.

The description of the observation sites is an important part of the GTN-P and should be based on existing ISO geospatial standards (ISO19115) in addition to collecting (when feasible) information on the surrounding environment such as vegetation, soil type, stratigraphy, geomorphology and geology. Air temperature and snow depth are often measured at monitoring sites as well as other climatic data to better characterize the microclimate. The soil moisture content may also be measured as it is an important factor determining the thermal behaviour of the ground. Changes in ice content are detectable by geophysical methods (Hilbich et al. 2008, Hauck et al. 2011). Variability of thermal conditions in boreholes due to variable surface cover and topography can be assessed using distributed miniature temperature loggers in the area of a borehole, which helps to assess representativeness (Noetzli et al. 2021). In most cases, off-the-shelf instrumentation can be utilized to make these measurements automatically and relatively inexpensively. Data are typically recorded by data loggers that can be downloaded during annual (or less frequent) visits to the site.

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