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Communication

Establishment of Permafrost Thermal Monitoring Sites in East Siberia

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Abstract: Permafrost lies close to the surface of the day, therefore, it is able to quickly respond to modern climatic changes. Under these conditions, the goal of understanding the evolution of permafrost in the near future requires monitoring studies of the current state of permafrost and, first of all, its thermal conditions. In this work, based on the experience of many years of research at the Melnikov Permafrost Institute of Siberian Branch of the Russian Academy of Science (MPI SB RAS), methodological and technical issues of equipping experimental sites for monitoring the thermal state of permafrost in Eastern Siberia are considered. It is demonstrated that the reliability of permafrost thermal monitoring depends not only on measurement devices used but also on proper borehole system design and adequate choice of a method for active-layer thickness measurement depending on soil composition and properties. The use of protective tubes significantly lengthens the life of sensors in soils. A method of protecting the loggers from surface waters is recommended.

Keywords: permafrost; ground temperature; active-layer thickness; datalogger; frost/thaw tube

1. Introduction

Documenting the current state of permafrost is increasingly important because of the observed global changes in climatic conditions. Observations of recent years indicate the ongoing degradation of permafrost in many regions of the world [1,2]. This implies certain risks for the living of the population and the stability of engineering structures in the permafrost zone. A key priority for this is to establish and maintain ground thermal monitoring which involves long-term continuous observations of the thermal parameters within the layer of annual temperature variations. For this purpose, a Global Terrestrial Network for Permafrost (GTN-P) was organized [3]. GTN-P is the primary international programme concerned with monitoring permafrost parameters. It was developed by the International Permafrost Association (IPA) under the Global Climate observing System (GCOS) and the Global Terrestrial Observing Network (GTOS), with the long-term goal of obtaining a comprehensive view of the spatial structure, trends and variability of changes in the active layer thickness and permafrost temperature. MPI SB RAS is a member of the GTN-P program. Establishment of permafrost thermal monitoring in MPI SB RAS is largely based on the methodological and technical recommendations developed by the GTN-P organizing committee.

Systematic observations of the permafrost temperature regime in East Siberia were begun in the 1930s at the Igarka, Yakutsk and Skovorodino permafrost stations [4]. They were continued in the 1960s–1970s at surface-balance research sites [5,6]. However, these investigations were of short duration and confined to the areas of the. At this time, temperature measurements of soils were made manually and were based mainly on the use of semiconductor thermistors as temperature sensors [7]. Due to permafrost near the surface, its temperature can even experience daily fluctuations, so monitoring of its temperature requires measurements several times a day. With manual measurement techniques, monitoring was only possible at permafrost stations.

Starting from the early 1990s, dataloggers—small digital devices for automated recording over time—have been increasingly used to measure physical parameters (temperature, pressure, moisture content, etc.) in different environments, including soils. Owing to the advances in microelectronics, they have become a mass product and are readily available off-the-shelf for research and industry. With the introduction of dataloggers, field stations no longer need permanent personnel to maintain observations. Temperature dataloggers have been extensively utilized by the Melnikov Permafrost Institute (MPI) since the early 2000s, allowing year-round ground temperature measurements in many regions across East Siberia (Figure 1).

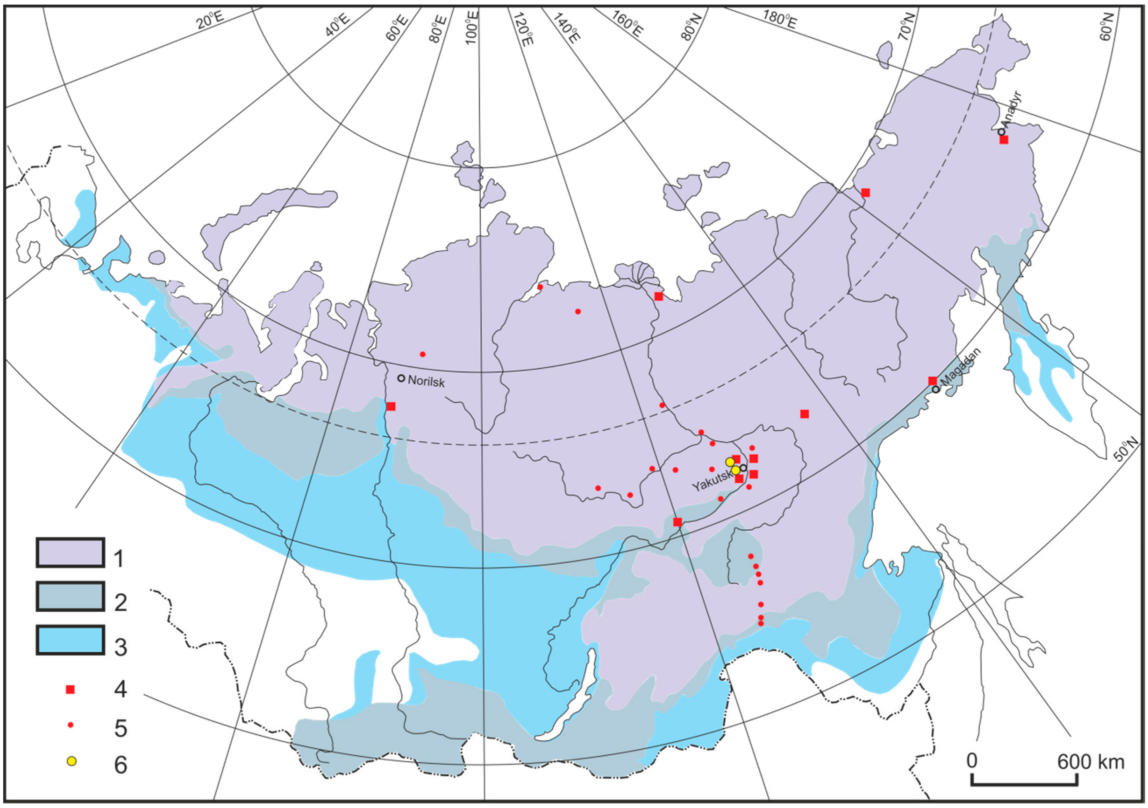

Figure 1. Map of monitoring sites for studying the thermal regime of the permafrost. Permafrost zones: 1–continuous; 2–discontinuous; 3–sporadic. 4–site with multiple monitoring points; 5–single monitoring point; 6–CALM site.

Industrial companies produce a wide range of automatic temperature recorders (dataloggers) now. Currently, there are already many scientific publications about the experience of using different datalogger models in geocryological research. Instrumentation selection, borehole system design and sensor configuration are extremely important considerations in developing thermal monitoring programs. The long-time performance of instrumentation, as well as the reliability of measurement data will be largely dependent on this. We see the importance of this work to introduce researchers to the experience of the MPI SB RAS on technical and methodological issues of creating experimental sites for monitoring the thermal state of permafrost in Eastern Siberia.

2. Methods

As noted in Introduction, automated data acquisition systems, including temperature dataloggers, are most convenient and effective for permafrost monitoring purposes.

Temperature dataloggers can be classified into two main categories: (1) expensive high-precision models and (2) off-the-shelf models at economy prices.

Precision dataloggers provide an accuracy of ±0.1 °C or better and have multiple (at least 8 to 10) channels. Such loggers have generally been specifically developed for research purposes. The most popular systems for meteorological and environmental monitoring applications include CR series multi-channel dataloggers from Campbell Scientific Inc. (Logan, UT, USA), DATAMARK dataloggers produced by the Hakusan Corporation (Tokyo, Japan) and YSI thermistors from Yellow Springs Instruments (Yellow Springs, OH, USA). In Russia, high-precision measurement systems for permafrost applications have been developed at several research and engineering centres, such as the Research Institute for Engineering Investigations and Construction (PNIIIS), the Scientific Research Institute for Hydrology and Engineering Geology (VSEGINGEO), the Research Institute of Space Instruments, Fundamentproekt Co. and the Institute of Geophysics UB RAS [8–11]. These systems commonly contain temperature sensors with long cables specifically designed for borehole measurements. However, the high cost of precision data loggers limits their wide use in permafrost research.

Economy-class data loggers are generally single-channel instruments (except for a few models) with a measurement accuracy in the range of ±0.2 to 1 °C. These dataloggers are mainly designed for ambient temperature control in industrial buildings, store facilities and cold chain (warehouses, refrigerators, etc.). The relatively low cost makes them attractive for permafrost monitoring projects. Among the devices of this category in geocryological studies are most often used UTL dataloggers from GEOTEST AG (Switzerland) [12–14], Tinutag dataloggers from Gemini Data Loggers Ltd. (Great Britain) [15], iButton dataloggers from Dallas Semiconductor (USA) [16], HOBO dataloggers from Onset Computer Corporation (USA) [17,18]. Our experience at MPI has shown that the HOBO U12-008 temperature datalogger manufactured by Onset Computer Corporation (USA) is the optimal model based on several criteria (measurement accuracy, number of measuring channels, cable length and price). This model also proved effective in studies conducted in north-European Russia and West Siberia [17,18]. HOBO U12-008 was also tested successfully in Alaska and recommended for ground temperature monitoring for the GTN-P program [19].

Permafrost monitoring is commonly planned to continue over long time periods spanning a decade or more [3]. It is therefore important to provide conditions for failure-free performance of dataloggers. Soil moisture and frost heaving are the most common reasons for sensor failure. Temperature probes in most logging systems utilize thermistors which are more sensitive to the harmful effects of soil moisture compared to other sensors [7]. Probe cables are made of copper wires, which have low tensile strength and can be damaged by stresses caused by tangential heave during freezeback of the active layer. The most reliable way to protect both from soil moisture and frost heave is placing the full length of the wire sensor(s) into a watertight protective tube (Figure 2) [20]. Small-diameter polypropylene pipes for plumbing systems are most suitable for this purpose. These pipes have excellent physical strength combined with resistance to repeated heating–cooling cycles and watertightness, therefore they can provide a good protection from both frost heave forces and soil moisture. Pipes with outer diameters of 20 and 25 mm and corresponding fittings are best suited for installing sensors of the data logger. To provide watertight connection, cap fittings should be attached to the tube by heat fusion using a butt fusion welder. After placing the wired sensor(s), the protective tube should be completely filled with non-cohesive material, such as dry sand, in order to prevent air convection. In highly frost-susceptible soils, temperature probes installed at shallow depths can be gradually displaced upwards (frost jacking) from year to year, resulting in the initial depth position of sensors to be changed. Even movement as small as a few centimetres can lead to significant misinterpretation of temperature measurements. In order to prevent long-term frost jacking in frost-susceptible soils, an outer anti-heave tube should be provided which would eliminate direct contact between the protective tube and the active-layer material. A gap between the outer and inner tubes is filled with a mineral grease to prevent potential adfreezing of the tubes. After inserting the tubing set, the borehole should be tightly backfilled.

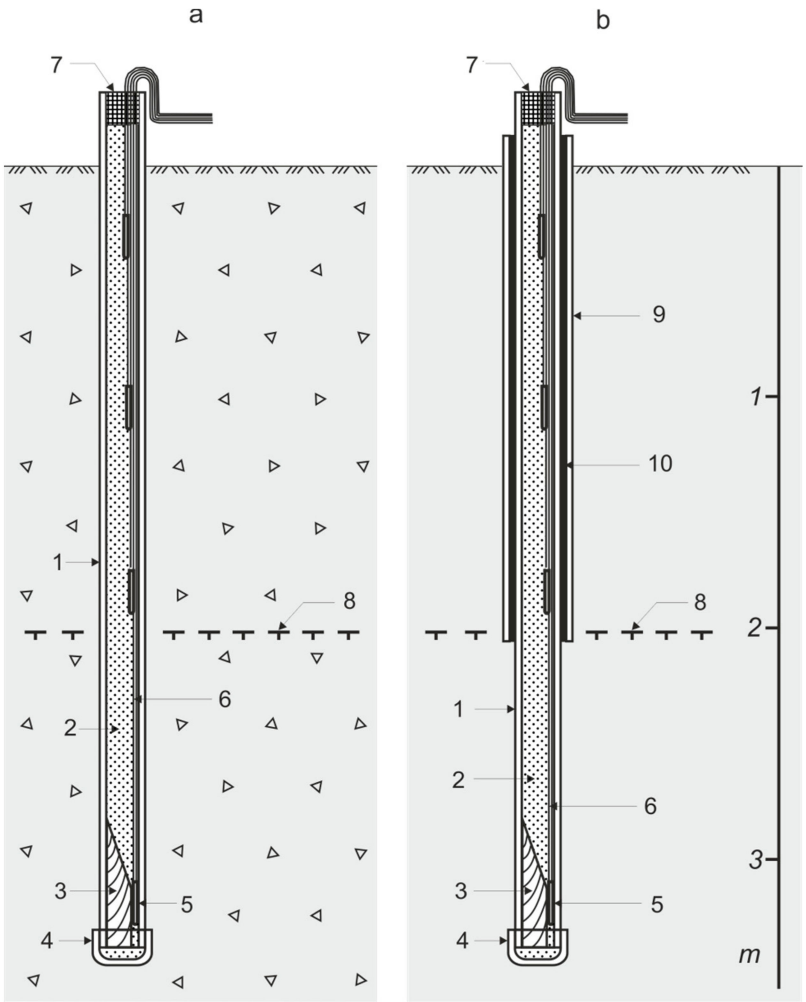

Figure 2. Design of a protective tubing case for datalogger sensors ((**a**)—for non-frost-susceptible soils, (**b**)—for frost-susceptible soils). 1—polypropylene tube; 2—sand; 3—wooden edge; 4—closure; 5—temperature sensor; 6—cable; 7-sealant; 8—active-layer base; 9—heave-protection tube; 10—grease.

Most dataloggers have a lower limit of the operating temperature range within −20 °C, so they need to be below the snow cover in winter. Dataloggers installed at monitoring sites should be protected from external impacts. The MPI's Laboratory of Permafrost Landscapes uses the following procedure to protect from penetrating surface waters (rainwater, melted snow water, flood water) into instrument casing. A hole, 20–30 cm in depth and 30–40 cm in diameter, is dug in the ground near the temperature borehole. The datalogger with attached sensor wires is placed at the hole bottom and covered with a metal cap with its diameter exceeding the lateral dimension of the logger (Figure 3). Household metal bowls can be used as a cap. It is impractical to use plastic caps because cracks may appear after one or two winters making the plastic not watertight. After placing the cap, the datalogger is buried. The use of this method of protecting the datalogger body on the flooded islands of the Lena River has shown reliable protection of the device against water penetration into the device during temporary flooding with a layer of water up to 4–5 m deep. This method proved to be effective in protecting the measurement system from surface fires as well.

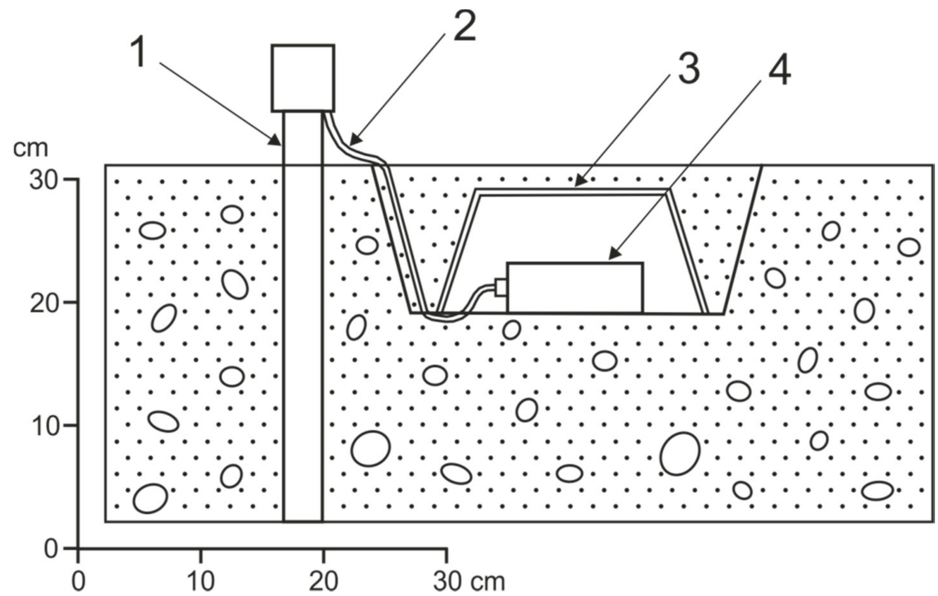

Figure 3. Schematic of data logger protection against flooding at the experimental site. 1-protective tube; 2-sensor cable; 3-metallic cap; 4-datalogger.

Active-Layer Thickness Monitoring Sites Instrumentation

Frost/thaw tubes have been used by the MPI's Laboratory of Permafrost Landscapes for many years to monitor active-layer thickness (ALT). The frost/thaw tube is a polypropylene pipe with an outer diameter of 25 mm and inner diameter of 20 mm, whose length exceeds the maximum possible thaw depth at a site. A polypropylene cap is welded on the tube bottom. The top end of the tube is covered with a removable cap to keep dust and insects from getting down inside. The sealed bottom is lowered into a small-diameter hole. The hole should be just deep enough for the tube to extend above the ground surface for 10–15 cm. The annulus is backfilled and thoroughly compacted. Then the tube is filled with distilled water to the ground surface level. Measurements are made by an extractable metal tape or rod whose end is lowered into the frost/thaw tube to the water/ice interface at the time of measurement. The difference between the tape reading and the length of the protruding part of the tube gives the depth to the 0 °C isotherm relative the ground surface.

Frost/thaw tubes have several important advantages. The primary advantage over mechanical probing is that measurements are made exactly at the same location each year which is important for long-term monitoring. Polypropylene tubes are resistant to cracking and splitting when water freezes inside them and are therefore well suited for long-term application. Determination of the 0 °C isotherm in the surrounding ground from phase change of water in the measuring tube provides a sufficiently reliable measurement, requires no preliminary calibration and has virtually unlimited time stability. Even if there is some difference between the position of the 0 °C isotherm determined by the thaw tube and the actual position of the phase boundary (or the top of plastic frozen soil in fine-grained material) due to different freezing points of the soil and the tube water, this will not affect statistical parameters of the time series since the error will be systematic. The absence of extractable components in the device eliminates air convection into the soil. Another important advantage is that potential frost jacking of the frost/thaw tube (to some threshold) has no effect on measurement accuracy. The entire water column within the measuring tube is frozen by the start of each summer season. Even if the tube level is changed, the water will thaw, in any given summer season, exactly as much as it is allowed by the heat content of the ground after the winter season and the summertime ground heat flow. The frost/thaw tube will be unsuitable for measurements only if its lower end has shifted up to the base of the active layer. Because of potential frost jacking of the frost/thaw tube over time, its lower end should be placed at least 1 m below the active-layer base. Installation of frost/thaw tubes is best done in the end of a warm season and measurements started in the beginning of next summer after the thermal disturbance has dissipated. Only in this case thaw tubes will provide reliable information.

3. Discussion

The factual material accumulated in Russia at geocryological stations by the end of the 90s of the last century shows that the response of the upper permafrost horizons to modern climate changes is highly dependent on landscape conditions [21–23]. Therefore, even in the same area but in different landscapes, opposite tendencies in the change in the temperature of permafrost can be observed. Hence, it follows that the conditionality of monitoring the thermal state of permafrost can be observed only if the observations cover the entire diversity of landscapes of the study area. This presupposes the equipment of many observation points rather than single ones. In practice, it is difficult to organize observations in all landscape types. But it is necessary to equip monitoring sites in the dominant landscapes of the study area.

On experimental sites, it is important to determine the mean annual ground temperature at the permafrost table ($MAGT_{PT}$) based on data loggers recording. Annual determination of $MAGT_{PT}$ make it possible to identify the direction of development of soils thermal state already in the first years after the change in surface conditions. In natural landscapes, it becomes possible to more clearly and reliably assess the impact of modern climatic changes on the permafrost and in the disturbed areas - the impact of various technogenic disturbances. Based on the results of the annual $MAGT_{PT}$ measurements, it is possible to identify, in advance, unfavourable tendencies in the development of the thermal state of technical object bases and make the necessary technological decisions (actions for artificial cooling of soils, etc.). The importance of controlling the long-term dynamics of $MAGT_{PT}$ in the study of the climatic change influence on permafrost evolution is noted by many researchers [24].

Measurement accuracy not less than ±0.1 °C can be provided only by precision dataloggers. Inexpensive economy-class dataloggers do not achieve such accuracy. There are works where the accuracy of dataloggers and sensors of different manufacturers was compared at the sites of geocryological monitoring (Table 1) [25]. As can be seen from the data given in the table, the Campbell datalogger, which belongs to the class of high-cost precision loggers, showed the best accuracy. The remaining models belong to the category of economy-class and their accuracy was ±0.2 °C. Compared to them, the manual method of measuring temperature with a multimeter is more accurate (±0.1 °C). In our studies in Eastern Siberia from precision models, good results on measurement accuracy (±0.1 °C) were shown by the DATAMARK datalogger of the Japanese company Hakusan Corporation with platinum resistance thermometers as sensors. Of the economy-class loggers, in our research we mainly use the HOBO U12-008 loggers, the accuracy of which we estimate is ±0.2 °C. In the methodological works on geocryology for temperature measurements in deep soil horizons, measuring instruments with an accuracy of at least ±0.1 °C are recommended [26,27]. Based on these recommendations, in the MPI SB RAS on experimental sites equipped with economy-class dataloggers (accuracy ±0.2 °C and below), a combined method for measuring soil temperature is used. Logger sensors are used to measure the temperature of the upper soil horizons, down to a depth of about 10 m. Observations of the temperature of soil deeper than 10 m are used manually with a multimeter and thermistors (accuracy ±0.1 °C). Reliability of determination of average values of physical parameters increases with increase of quantity of initial data of automatic measurements because influence of random errors of large amplitude decreases and there is mutual compensation of deviations of opposite direction [28]. When using data loggers, the determination of average temperature values over long time intervals (month, year) is obtained from thousands of individual measurements. The accuracy of ±0.2 °C of the economy-class dataloggers is quite sufficient to obtain the conditioned values of the average monthly and average annual temperatures.

Table 1. The accuracy of the different instrument types.

Measurement Method	Instrument Type	Accuracy, °C
Manual	Thermistors connected to multimeter	±0.1
Automatic	Campbell data-logger	±0.05
	M-Log7 datalogger	±0.2
	Tinytag datalogger	±0.2
	HOBO U22 datalogger	±0.2
	Lakewood datalogger	±0.2

Special-purpose studies conducted in several regions of the permafrost zone have demonstrated that convection in the boreholes which are in an air-dry state or filled with non-freezing fluid results in significant errors in temperature measurements observable down to depths of 5–10 m from the ground surface (Tables 2 and 3) [29,30]. In our opinion, dataloggers with wired sensors are the most suitable for geocryological studies, which allow installing sensors in boreholes with subsequent backfilling with soil. In this case, air convection into the borehole with installed sensors is excluded. It is also preferable to remove the casing. If the monitoring program involves measurements at greater depths (below 10 m) using the portable equipment with static probes on cables, the main borehole can be left in an air-dry state or filled with non-freezing fluid. A shallower borehole is drilled nearby for permanently installing the data-logger sensors, which then should be backfilled. The boreholes should be spaced at least 3–4 m apart, so that thermal disturbances around the deeper borehole caused by convective heat transfer would not affect temperature readings in the shallower borehole.

Table 2. Extreme and annual differences between the natural ground temperature and the temperature in an air-dry borehole with a 50 mm diameter and metal casing, Yakutsk.

Depth, m	Winter	Summer	Annual Average
1	−5.3	0.9	−1.2
2	−2.6	0.8	−1.0
3	−1.2	0.3	−0.7
10	−0.2	0.0	−0.1

Table 3. Annual range of temperature departures in the boreholes cased with polyethylene pipes 50 and 100 mm in diameter, Yakutsk.

Depth, m	Annual Range, °C	
	50 mm Diameter	100 mm Diameter
0.5	0.8	4.7
1.0	0.7	2.9
1.5	0.2	2.2
2.0	0.1	1.7
2.5	0.0	0.7
3.0	0.0	0.2
4.0	0.0	0.1

Presently, three field methods are commonly used in the international permafrost monitoring programs to measure the thickness of the active layer: mechanical probing with a metal rod or a soil auger, soil temperature profiles and frost/thaw tubes [19,31,32]. The choice of a method for long-term monitoring depends on material composition and properties in the study area. Probing with a metal rod is best suited for moist soils in the tundra and northern taiga zones, as well as for boggy soils of the forest zone. The method is not applicable to the areas where stones comprise over half of the material. It is also undesirable in relatively dry soils with deep thawing where probing is physically hard and can yield inaccurate estimates. For example, desiccated sand layers, even in a thawed state, are resistant to rod insertion and the permafrost surface may not be detected confidently. The primary disadvantage of mechanical probing for long-term monitoring in dry soils is that it disturbs the soil structure, leaving voids that persist for long time. This inevitably modifies the natural soil moisture regime. For the same reason, soil augers are also not a good choice for monitoring studies, although they can penetrate dry soils more easily compared to rods. Under such conditions it is preferable to use frost/thaw tubes or temperature records from sensors permanently installed in the active layer. Based on these considerations, near Yakutsk, where dry soils prevail, two CALM sites (R42 and R43) were equipped with a dense network of frost/thaw tubes.

In mountainous terrain, the establishment of a monitoring network is challenged by the cost and difficulty of drilling. Where drilling is not feasible, thermal monitoring can be implemented utilizing temperature dataloggers. MPI has established and maintains several sites in the mountains of East Siberia where sensors of the dataloggers are placed at shallow depths (1–1.5 m) by digging pits. The pits are backfilled after sensor installation. Mean annual ground temperatures obtained annually at these depths are sufficient to assess recent trends in permafrost temperature in relation to observed climatic changes.

4. Conclusions

When using automatic temperature recorders in geocryological studies, the accuracy of the equipment used should be taken into account. Precision dataloggers can be used to measure temperature over the entire depth range. Economy-class dataloggers with an accuracy of ±0.2 °C and below are best used for temperature measurements in the upper soil horizons. For geocryological studies, dataloggers with wired sensors should be preferred, which allow installing sensors in boreholes with subsequent backfilling with soil to prevent air convection. The most reliable way to protect of datalogger sensor(s) from soil moisture and frost heave is placing the full length of the wire sensor(s) into a watertight protective tube.

A method for active-layer thickness measurement at long-term monitoring sites should be selected based on soil composition and physical properties of the active layer. Mechanical probing with a metal rod or soil auger is not desirable in areas dominated by stony soils or dry soils with deep freezing. Here, preference should be given to frost/thaw tubes or temperature records from sensors permanently installed in the active layer.

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