The Verkhoyansk Range Permafrost Monitoring Network, eastern Siberia

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ABSTRACT

Ground temperature regimes have important influences on hydrological, geomorphological, and biological processes in the East Siberian Mountains, but the area has been less studied than other regions with mountain permafrost. To help fill this knowledge gap, permafrost studies have been started in 2010 along a 62-63°N longitudinal transect that crosses the Verkhoyansk Range at elevations between 283 and 1821 m. Based on the long-term monitoring, it was established that, mean annual ground temperature at the depth of 1 m ranges between -1.1 and -10.1 °C, while maximum active layer thickness varied from 0.3 m to 2.6 m depending on the landscape. Three 30-m and one 20-m permafrost temperature-monitoring boreholes were established near weather stations in August 2022 to determine the depth of zero annual amplitude, cryostratigraphy, thermal properties and environmental factors influencing the ground temperature regime. A borehole situated in the famous Oymyakon village, the coldest place in Siberia, and another borehole in Central Yakutia are used for inter-sites comparison. In addition, a 6.7 m deep borehole drilled in August 2021 in a floodplain recorded a talik thermal regime. This showed that substrates near large rivers freeze seasonally to ~5.5 m and may warm to +6 °C by flow of water through the permeable layer. Notwithstanding severe climate conditions in eastern Siberia, the permafrost state influenced by numerous mountain environment gradients has distinctive patterns. However, without scaling comprehensive and integrated research, this area will remain on the permafrost study's periphery.

1 INTRODUCTION

East Siberia has a severe climate, one of the coldest globally. Permafrost ecosystems in the region are particularly sensitive to climate change and their evolution has already had significant impacts on river discharge (Makarieva et al. 2019), livelihoods (Lytkin et al. 2021), the sustainability of infrastructure, geomorphological processes and slope stability.

This study focuses on the Verkhoyansk Range and adjacent territory, where there is a relative paucity of permafrost studies (Figure 1). The key features of this region are extremely low air temperatures (down to -60 °C in winter), complex terrain and high geothermal heat flux (up to 0.1 W m^{-2}). Mean annual air temperatures at numerous meteorological stations have risen at rates of 0.3–0.4 °C/decade (Gorokhov and Fedorov 2018), but the temperature regime of permafrost has remained unknown until recently.

Permafrost conditions were determined in the 1960s and 1970s at a few sites, mostly using deep boreholes (Figure 1). Those investigations showed that permafrost is continuous with thicknesses from 100 to 600 m and that temperatures at the depth of zero annual amplitude (D_{zaa}) range from -9 to -2 °C (e.g., Nekrasov 1976).

The contemporary stage of permafrost study in this region was resumed by the high-mountain monitoring network, which has been established in 2010 (Sysolyatin et al. 2020) and the further extension of the ESPT boreholes network project (Sysolyatin et al. 2023), focused on permafrost temperature monitoring near the governmental meteorological stations. To date, the sites located between 132°E and 145°E are unified. Overall, the thermal state of permafrost is stable, but at some areas thermal state is close to 0 °C, and at floodplain only seasonal freezing occurs. Recent results allow to improve the permafrost features of a huge territory of Asian northeast.

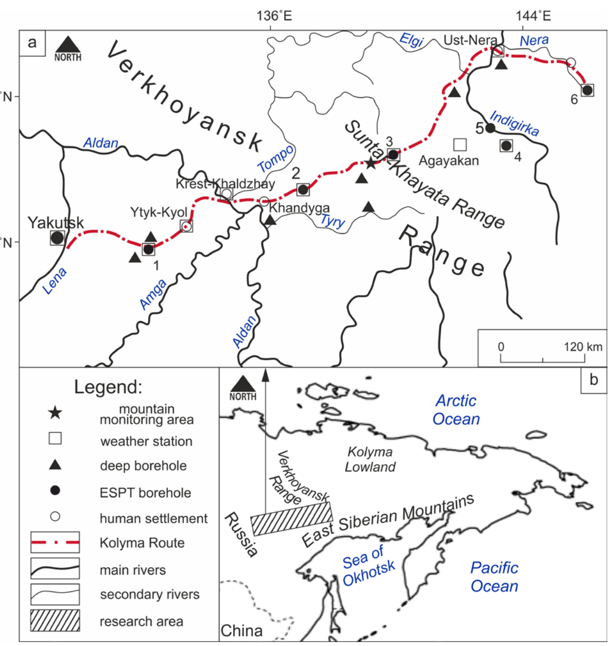

Figure 1. (a) Location of study sites within the Verkhoyansk Range and adjacent areas. ESPT boreholes: 1. Churapcha; 2. Tyoply Klyuch; 3. Vostochnaya; 4. Tomtor; 5. Oymyakon; and 6. Delyankir. (b) Location of study area in eastern Asia.

2 STUDY AREA

The Verkhoyansk Range stretches roughly 1000 km from the Lena Delta at the Laptev Sea coast in the north to the Yudoma-Maya Highlands in the south. The landscape of this region comprises smooth mountains with vast intermontane basins separated by numerous rugged ridges. The Kolyma Route, connecting Yakutsk and

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Magadan, crosses the middle of the range and was used to establish several weather stations during WWII. This route is favourable for permafrost temperature monitoring since it provides access to a variety of environmental gradients. Elevations along the route range from 94 to 1303 m a.s.l and adjacent peaks rise to 2300–2500 m a.s.l. Substrates are typically ice-rich Quaternary sediments of glacial origin up to 30 m thick, underlain by bedrock of Upper Paleozoic and Mesozoic age.

3 Methodology

Air, surface and shallow (up to 5 m deep) ground temperatures of the high-mountain environment have been monitored since 2010 at 15 sites at elevations of 850 to 1,821 m a.s.l in the Suntar-Khayata Range using Onset HOBO loggers (U22-001, U23-001, U12-008 with TMC50-HD sensors). Due to a variety of reasons (mainly by the wild animals invade) only a limited number of sites are suitable for presenting (Table 4).

The East Siberia permafrost transect (ESPT) project dates are from 2022. The aim is to establish the ground temperature regime at the main weather stations and to identify the factors controlling the permafrost thermal state in the Verkhoyansk Range. Five boreholes with depths of up to 30 m were drilled (with core sampling) in August 2022. Temperatures were measured using Russian-manufactured "Impedans" logger systems with calibrated ADT7410 sensors. Calibration took place under simulated winter conditions (-25 °C) in a TERMOTEST-100 chamber where temperatures can be controlled with an accuracy of 0.01 °C. The HOBO and Impedans logger systems had +0.1 and -0.15 offsets, respectively (Table 1).

Table 1. Temperature test of logger systems with ambient temperature at -25 °C.

Temperature calibration chamber, °C	HOBO, °C (TMC50-HD)	Impedans, °C
10	10.05	9.85
5	5.06	4.85
3	3.06	2.88
1	1.08	0.86
0	0.08	-0.12
-1	-0.91	-1.13
-3	-2.89	-3.13
-5	-4.90	-5.11
-10	-9.88	-10.12

4 Results

4.1. Verkhoyansk Range

4.1.1. ESPT preliminary data

Conditions in the Verkhoyansk Ranges are represented by the Vostochnaya, Tomtor, Oymyakon and Delyankir permafrost monitoring sites. With the exception of the Oymyakon site, these are all located close to a weather station (Table 2). Data are available for mid-September 2022 to mid-August 2023 except for Oymyakon where loggers failed in June 2023. The results are presented as temperature profiles in Figures 2 and 3, and the main parameters are in Table 3.

Vostochnaya is the highest monitoring site and it experiences the most moderate air and ground temperature regime. The absence of vegetation leads to relatively thick active layer, even though snow cover was present at this site for more than 70% of the study period. At the end of summer, the thick of active layer exceeds even Central Yakutia's site — Churapcha (Figure 3).

The Tomtor and Oymyakon study sites are located at similar elevations within Oymyakon valley, but the former has a surface cover of grasses and the latter is forested. These locations experience extremely low air temperatures in winter and have relatively thin snow covers. The open Tomtor site has a thinner active layer and colder permafrost than the Oymyakon site (Figure 2).

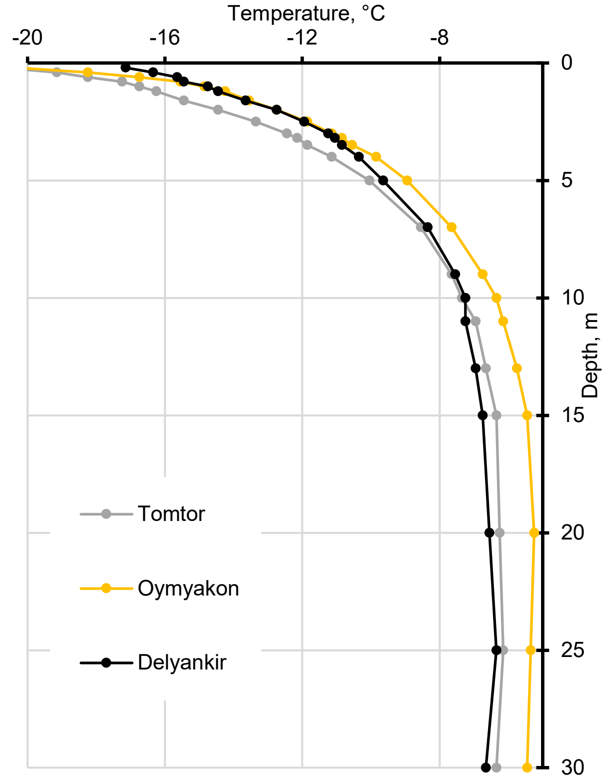

Figure 2. ESPT borehole minimum temperature in the 2022/2023 winter period.

Delyankir is the coldest ESPT monitoring borehole in the Verkhoyansk Range. The lowest air temperature, a moss vegetation cover and the shortest snow cover period result in the thinnest active layer (0.8 m) and the coldest permafrost temperature at D_{zaa} (-6.7 °C). Although Delyankir has the greatest air temperature amplitude, the D_{zaa} at this site is shallower than at the other sites.

Overall, the temperature profiles at end of thaw period below 15 m are similar despite differing environmental conditions (Figure 3). The minimum surface temperature ranges from -20.8 to -17.2 °C, while the D_{zaa} temperatures are around -6 °C. The refreezing time continues until the end of November (Table 3).

Table 2. Meteorological station site characteristics from 2005 to 2022.

Site	Elevation, m (a.s.l.)	Location (lat/long)	MAAT, °C	Air temp. amplitude, °C	Mean air temperature for January, °C	Vegetation
Churapcha	186	N 61° 58’ E 132° 25'	-8.8	89.8	-40.0	Grass
Tyoply Kluch	289	N 62° 48’ E 136° 54'	-9.9	93.4	-40.7	Larch forest and mosses
Vostochnaya	1288	N 63° 14’ E 139° 38'	-12.1	82.5	-34.5	Sporadic mosses and grass
Tomtor	740	N 63° 15’ E 143° 11'	-14.1	94.1	-45.4	Grass
Oymyakon	682	N 63° 28’ E 142° 46'	~ -14.1	~ 94.1	~ -45.4	Sparce larch wood and grass
Delyankir	801	N 63° 51’ E 145° 36'	-14.5	94.1	-43.1	Larch wood with thick mosses

Table 3. Main parameters at the studied meteorological stations in 2022/2023 study period.

Site	Winter air daily min, °C (date)	Sum of negative daily temperature, °C	Max snow depth, cm	Days with snow cover	Min surface temp (0.2m), °C (date)	Min temp at top of permafrost*, °C (sensor depth)	Date of complete refreezing**
Tyoply Kluch	-52.9 (17.01.2023)	-5588	82	215	-12.3 (26.02.2023)	-1.7 (7 m)	11.02.2023
Vostochnaya	-45.6 (10.12.2022)	-5778	53	256	-19.0 (15.02.2023)	-	~ 25.11.2022
Tomtor	-58.9 (12.12.2022)	-6852	34	192	-20.8 (26.02.2023)	-16.3 (1.2 m)	01.11.2022
Oymyakon	~ -58.9	~ -6852	~ 34	~ 192	-20.4 (26.02.2023)	-13.6 (1.6 m)	21.10.2022
Delyankir	-58.8 (12.12.2022)	-6882	40	176	-17.2 (26.02.2023)	-15.5 (0.8 m)	08.10.2022

* is almost comparable to the thickness of the active layer
** the date when all sensors on the temperature’s string are fixed the negative values

4.1.2. High-mountain monitoring sites.

Despite the differences in the sites, the air temperatures within the high-mountain monitoring area were 3–4 °C warmer than at the Vostochnaya meteorological station. Likewise, a lapse rate is present as a result of inversion — from 800–900 to 1300–1400 m, it is positive, and as altitude increases, it slightly decreases. Nevertheless, the relation between altitude and ground temperature is less distinct. Selected sites set and ground temperature are summarized in Table 4. The stone stream temperature regime is close to the air temperature due to less snow and the chimney effect. Meanwhile, the features related to the incoming solar radiation result in relatively high temperatures at the mountain peaks, taking into consideration the cooling effect of air temperature inversion and triangle shape of peak. Snow is highly variable inter-annually at the elevation and led to the sharp shifting of 1 m depth ground temperature (e.g., the lateral moraine site). The floodplain site is influenced by groundwater heat transfer resulting in the warmest ground temperatures.

Table 4. Shallow depth monitoring sites, the Suntar-Khayta Range.

Elevation, m (a.s.l.)	Landform	MAGTs at 1 m depth, °C (min/max)	Available data*
1750	Mountain peak	-5.2/-5.2	2016-17
1586	Flat field (peneplain)	-5.9/-5.1	2016-17
1209	Saddle (mountain pass)	-6.9/-6.0	2016-17
1011	Stone stream (kurum)	-10.4/-8.4	2014-20
916	Lateral moraine	-5.0/-2.6	2013-19
896	Floodplain valley	-2.6/-0.8	2013-20

*entire calendar year

The ground temperature at a depth of 1 m in particular sites can vary with an amplitude around 40 °C. The average annual temperature ranged from -0.8 to -10.4 °C. The thickness of the active layer varied from 0.5–0.7 m to 1.8–2 m. The minimum values occurred in wet areas with a moss cover. The thickness of the active layer within the moraine deposits varied from 1.5–1.7 m, whereas on mountain peaks due to a shorter period of positive temperatures it almost exactly does not exceed about 1.2–1.4 m.

The minimum average surface temperature (exclude kurums) from July 2017 to July 2018 was -8.8 °C at a site with an elevation of 936 m. The temperature on the surface of the southern slope in the cold season can drop to -42.2 °C. Sites in the valley and on the northern slope, at an elevation of 1209 m, have an average surface temperature of -7.1 °C. The highest average surface temperature (-6.1 °C) for the selected period was for the site at an altitude of 1750 m.

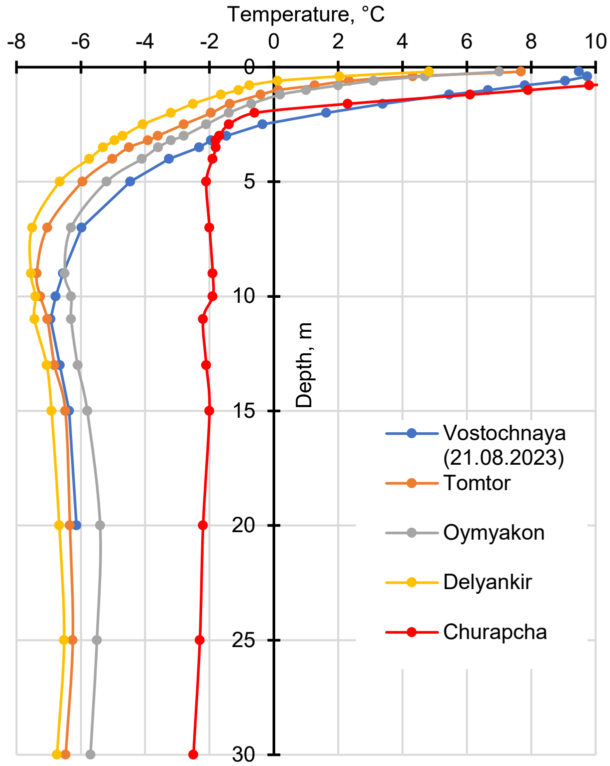

Figure 3. Ground temperature profiles in the ESPT boreholes on 15.08.2023. Note: Tyoply Klyuch shown separately due to logger failure.

4.2. Verkhoyansk Range foothills

Tyoply Klyuch has been selected for permafrost characteristics on the west slope of the Verkhoyansk Range. Unfortunately, logger failure has interrupted data collection on 24.05.2023, and we are connecting this event with spring snowmelt. Ground temperatures at the Tyoply Klyuch site in a larch forest were quite high despite low air temperatures, with a MAAT around -10 °C (Table 2). Permafrost temperatures below 11 m almost do not change and fluctuated around -1 °C during the study period (Figure 4). A huge impact on the temperature regime was made by seasonal groundwater flow and convection heat exchange in the upper layer. A month after drilling the borehole, when the heat disturbance becomes negligible, the active layer thickness was found to be 5–7 m. Furthermore, the significant thickness of the snow cover is also contributing to a relatively warm temperature regime. Thus, Tyoply Klyuch is the warmest site east of the Aldan River with permafrost persistence.

4.3. Central Yakutia

The ESPT project includes a monitoring borehole site near the Churapcha weather station that represents permafrost condition in Central Yakutia. This borehole was drilled in June 2023 and temperatures were measured on 15.08.2023 (Figure 3). Ground temperatures downwards from the base of the ~1.9 m active layer were about -2 °C, significantly warmer than at the Verkhoyansk Range sites. Permafrost temperatures slowly decreased below 20 m. A similar temperature curvature pattern was recorded in a ~600 m deep borehole in the same area (Kirillin et al. 2022). The effects of agricultural activity and a warming climate resulted in the lowest permafrost temperature being observed only at depths of 150–200 m.

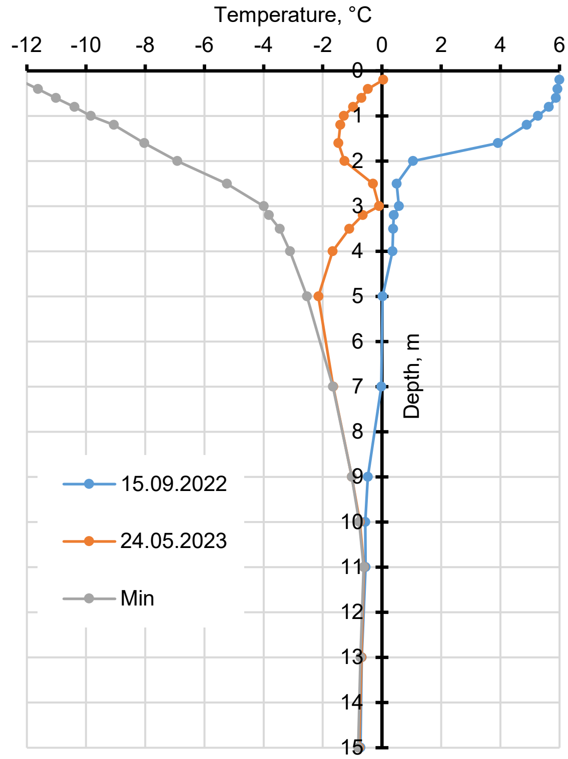

Figure 4. Tyoply Klyuch ground temperatures after the disappearance of heat disturbances from drilling and at the last moment of measurements. Minimal temperatures also provide for each depth correspond to various dates.

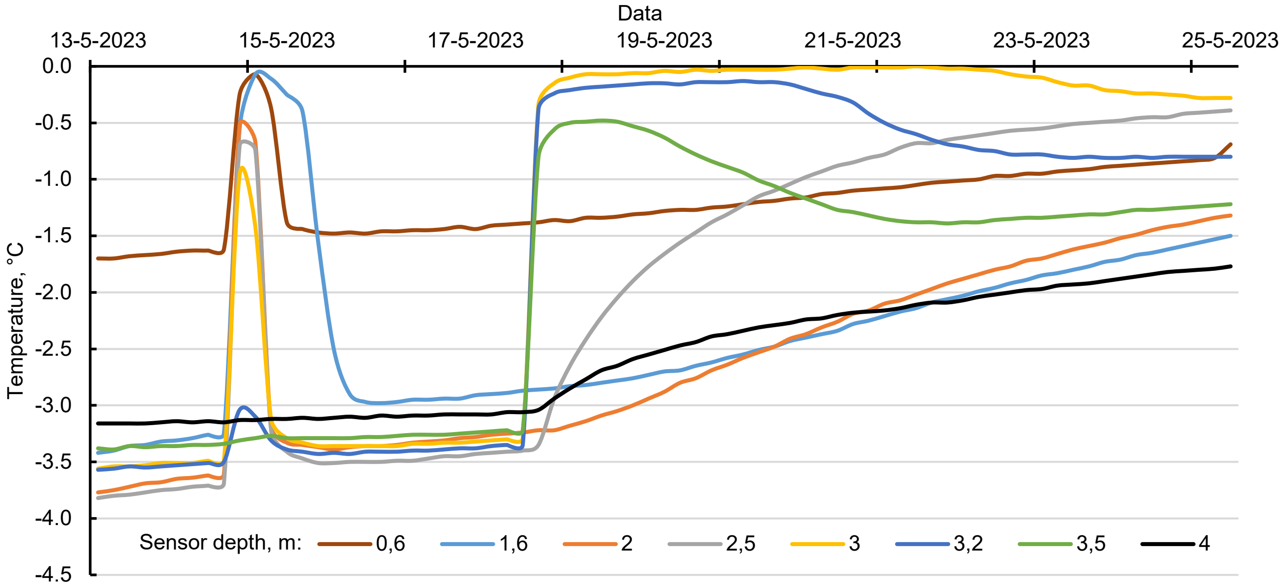

Figure 5. Groundwater infiltration event and its impact on the thermal regime on the Tyoply Klyuch site.

5 Discussion

Macroclimate, and MAAT itself to a greater extent, is a major control on the permafrost temperature regime of the Verkhoyansk Range. Generally, the latitude and longitude increasing decreases air/ground surface temperatures and reduces the summer period that creates severe climate conditions. As a fact, as the winter months' mean temperature does not rise above -35 °C, the D_{zaa} temperature around -6 °C is quite justified. However, the specific sites have active layer thickness up to 2.5 m enlarged by incoming radiation. The floodplain substrate can only be seasonally frozen, and below 5–6 m it remains unfrozen: in general, the territory covered by the thermophyte plants (e.g., poplar).

For the 2022–2023 initial monitoring period of the ESPT project, the moment of the subsurface minimum temperature within the study sites has been found. Despite the lowest air temperature being detected synchronously in the second decade of December 2022, the subsurface sensors on the remote sites have been detecting minimums at the one time but in February (Table 3). Tomtor meteorological station is the only on Oymyakon valley and characterized by lowest subsurface and top of permafrost temperatures due to extremely low snow cover depth in study period. However, low thermal diffusivity of the Delyankir site soil prevents ground thawing more than 0.8 m.

High-located sites (Vostochnaya) experienced the complex influence of air temperature inversion, incoming solar radiation, and groundwater evaporation. This led to a thick active layer, whereas ground temperatures below 10 m are similar to those at eastern ESPT sites. Similar features were reported by Throop et al. (2012) for the Sixty Mile site.

For the high-mountain environment the huge differentiation is typical. A variety of elevation, aspect, soil and rock material, vegetation etc., influence on the ground temperature regime. The landforms are more useful for assessing ground temperature regime, at least at shallower depths (Table 4). Indeed, the stone streams slopes (kurums) is colder due to the chimney effect despite of the valley location (Gorbunov et al. 2004). In turn, the floodplain is the warmest ground temperature regime caused by groundwater flow and the permeability of the sediments. The feature of seasonal thaw is crucial for slope stability and road infrastructure sustainability. For mountain areas, floodplain, and high roughness parts, there is a potential risk.

The Verkhoyansk Range foothills encompass a huge territory east of the Aldan River. At Tyoply Klyuch, the bedrock is overlain by 15–20 m of coarse-grained till sediments. At a depth of 3 m, a viable pathway for groundwater flow occurs during the snowmelt season, disturbing the thermal regime. Indeed, a slight positive temperature at D_{zaa} proves the repeating nature of this process. In Figure 5, a 3 m depth sensor immediately responds to penetrating water moving in the zero-curtain zone, while upward sensors remain at negative temperature values.

The Central Yakutia is the dramatic example of ice-rich permafrost degradation (Lytkin et al. 2021). The evolution of surface energy balance led to harmful consequences for rural dwellers. A single measurement of Churapcha borehole shown a dreary outcome of husbandry activities on the cryolithozone.

6 Conclusions

The presented monitoring network has potential for prolongate it to eastward and can be scaling next to meteorological station on crucial landforms. To date, the main results include:

1. The permafrost is stable with quite low temperatures through most of the Verkhoyansk Range, with the exception of sites affected by groundwater flow.
2. Despite the famously severe climate of the Oymyakon valley, lower permafrost temperatures were observed elsewhere at similar elevations and in similar geomorphological settings.
3. Permafrost was absent beneath alluvial gravel deposits in a floodplain and was present but with relatively high temperatures in the foothills.
4. Assessing the response of permafrost in the region to climate warming remains a major challenge. We have taken the first steps by developing a baseline monitoring network that can be used for further engineering or scientific investigations.

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