EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth's Cryosphere, 2023, vol. XXVII, No. 2, pp. 3–13

GEOTHERMAL FIELDS AND THERMAL PROCESSES IN CRYOSPHERE

GROUND TEMPERATURE AT THE DEPTH OF ZERO ANNUAL AMPLITUDE IN THE AREA OF SUPRAPERMAFROST TALIKS IN CENTRAL YAKUTIA

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Despite the low mean annual air temperature and low precipitation, subaerial suprapermafrost aquifer taliks are formed in some cases in the continuous permafrost zone of Central Yakutia. The paper presents an analysis of the seasonal and interannual dynamics of ground temperature in contrasting geocryological conditions – in areas of permafrost spread from the surface and in suprapermafrost subaerial taliks – of the key site Levaya Shestakovka 20 km southwest of Yakutsk. The permafrost table in this area occurs at depths from 0.5 to 20 m. The highest ground temperatures are typical of the aquiferous suprapermafrost taliks confined to gentle slopes composed of sandy sediments and covered with pine woodland. The thickness of the seasonally frozen layer reaches 3 m, and the depth of zero annual amplitudes varies from 6 to 12 m. Thawed deposits are preserved due to the continuous filtration of groundwater in them. The lowest ground temperatures are characteristic of the mire and the river floodplain. The depth of seasonal thawing varies from 0.5 to 1.0 m, and the depth of zero annual amplitudes exceeds 15 m. In recent years, slow freezing of the taliks from below has been noted due to mild cooling of the strata underlying the thawed aquifers. Beyond the area of taliks, weak multidirectional changes in ground temperature have been recorded.

Keywords: *suprapermafrost taliks, temperature at the depth of zero annual amplitude, Central Yakutia, sand deposits, groundwater, seasonally thawed layer, seasonally frozen layer, continuous permafrost.*

Recommended citation: Lebedeva L.S., Baishev N.E., Pavlova N.A., Efremov V.S., Ogonerov V.V., Tarbeeva A.M., 2023. Ground temperature at the depth of zero annual amplitude in the area of suprapermafrost taliks in Central Yakutia. *Earth's Cryosphere* XXVII (2), 3–13.

INTRODUCTION

Permafrost, common in Central Yakutia, has a thickness of 200 to 700 m [*Anisimova, 2003*]. The continuity of the permafrost zone is interrupted by through taliks under large lakes and the Lena River bed. The depth of seasonal thawing of rocks varies from 0.3 to 4.5 m and depends on the type of landscape [*Pavlov, 1979; Anisimova et al., 2005; Varlamov, Scryabin, 2012*]. In the basins of the Lena and Vilyui rivers, the existence of local subaerial suprapermafrost aquifers is known [*Ponomareva, 1999; Boitsov, 2002*]. The temperature regime of the rocks in them differs from the surrounding area. Under natural conditions, near the city of Yakutsk, the temperature of water-bearing sandy sediments of the suprapermafrost talik in the depth interval of 3–6 m is about 0°C throughout the year [*Lebedeva et al., 2019*]; outside the talik, it reaches –6.6°C [*Varlamov, Skryabin, 2012*]. In the Vilyui River basin, in areas composed of eolian sediments from the surface and covered with bearberry-lichen pine forest, the thickness of the seasonally frozen layer (SFL) above the taliks is 2.5–4.5 m [*Ponomareva, 1999; Lytkin et al., 2018*]. The seasonal and interannual regime of rock temperature in the areas of talik development and beyond remains poorly studied to date. Questions of the genesis, distribution, geometry, and seasonal and interannual dynamics of taliks are rarely raised [*Shepelev, 2011; Anisimova, Pavlova, 2014; Galanin, 2015; Semernya et al., 2018*]. The response of rock temperature in areas with widespread suprapermafrost taliks to climate warming has not been determined.

It is known that the current increase in air temperature leads to uneven degradation of the upper part of permafrost. Over 25 years of observation at the end of the 20th century, no increase in the thickness of the seasonally thawed layer (STL) was found in the peatlands of the north of Western Siberia [*Moskalenko, 1998*]. According to [*Vasiliev et al., 2020*], in the southern tundra and forest tundra of Western Siberia, the permafrost table subsided by 2–10 m; in the northern taiga zone, by 4–6 m: in some areas, suprapermafrost taliks were formed. In the northeast of the European territory of Russia, observations on hummocky peatlands over a five-year period showed that the thickness of the STL is increasing [*Kaverin et al., 2019*]. In the Timan-Pechora region, the retreat of the southern permafrost boundary to the north has taken place since the 1970s. By 2008, it shifted to the north by 30–40 km in the Pechora Lowland, and up to 80 km on the denudation plains of the Cis-Ural region [*Oberman, Lygin, 2009*]. The area of continuous permafrost has decreased due to the appearance of new taliks and transition to discontinuous permafrost.

In northern Yakutia, there has been a tendency for an increase in the temperature of rocks in the tundra and taiga since the late 1990s [*Fedorov-Davydov et al., 2018*]. According to [*Boike et al., 2019*], the temperature of the rocks at the bottom of the annual heat transfer layer has increased since the early 2000s by 2–3°C. In some years (2007–2008 and 2010–2011), the depth of seasonal thawing of rocks increased by 10–20% of the norm.

An intensive increase in air temperature has been observed in Central Yakutia since the mid-1960s [*Gorokhov, Fedorov, 2018; Neradovskii, 2020*]. Meanwhile, some researchers note that an increase in the thickness of the STL and in the temperature of frozen rocks is weakly expressed [*Pavlov et al., 2002; Varlamov et al., 2020*]. The modern period as a whole is characterized by sufficient thermal stability of both high-temperature and low-temperature permafrost [*Varlamov et al., 2021*]. Other authors show that rock temperature in open (forestless) areas has increased by up to 0.5°C over the past three decades with a simultaneous increase in the depth of seasonal thawing, activation of thermokarst subsidence in areas of the development of wedged ice and suffusion processes in areas of discharge of intrapermafrost waters [*Fedorov et al., 2014; Gagarin et al., 2016*].

In south Yakutia, the thickness of the STL does not change significantly [*Zabolotnik S., Zabolotnik P., 2014*]. In many other regions of the permafrost zone, against the background of global climate warming, the mean annual permafrost temperature decreases, the ice content of rocks increases, and the thickness of the STL decreases [*Konishchev, 2009; Biskaborn et al., 2019*]. The aim of this work is to analyze the seasonal and interannual dynamics of rock temperature in contrasting geocryological conditions – in areas of permafrost spread from the surface and of suprapermafrost subaerial taliks within the key site of Levaya Shestakovka 20 km southwest of Yakutsk.

OBJECT OF STUDY

The Levaya Shestakovka site with an area of about 1 km^2 is located in the basin of the Shestakovka River, a small left tributary of the Lena River, on a gentle slope of a denudation plain with absolute heights of 190–210 m asl [*Shepelev et al., 2002*] (Fig. 1).

The climate of the study area is sharply continental with severe long winters and short hot summers. The mean annual air temperature at the nearest weather station in Yakutsk for the period of 1920–2019 is –9.5°C; the mean monthly air temperature in January is –40.5°C; in July, +19.1°C. The mean annual precipitation from 1937 to 2015 is 268 mm/yr, including 160 mm/yr of rainfall, 100 mm/yr of snow, and 8 mm/yr of mixed (liquid/solid) precipitation [*Bulygina et al., 2022a,b*].

Larch-birch forests grow in ravines and depressions and on level surfaces. Pine forests occupy mainly slopes and divides. Mires and swamps are developed along streams and lakes.

The upper part of the geological section down to a depth of 30 m is composed of loose sandy sediments with few clayey interlayers [*Boitsov, 1985*]. On the slopes and divides, fine- and medium-grained sands predominate. Their volumetric moisture content in the aeration zone does not exceed 2–8%. Sandy sediments have a quartz–feldspar composition; their bulk density is more than 1.70 g/cm^3, and their porosity is 33–35% [*Boitsov, 2002*]. Moistened (15–25%) sands are overlain by an organogenic layer in the bottoms of the valleys of streams and ravines [*Skryabin et al., 1999*].

The territory under consideration belongs to the area of development of non-stationary frozen strata, the thickness of which in the modern period reaches 400–500 m. The temperature of rocks at a depth of 100 m is from –0.6 to –1.0°C [*Boitsov, 1985*], and at the bottom of the layer of zero annual amplitudes, depending on the landscape, it varies from positive (close to 0°C) values to –2...–3°C and below [*Varlamov, Skryabin, 2012*]. The thickness of the STL varies from 4 m on gentle slopes and divides under pine forests to 0.5 m in mires. On the right-bank terrace of the Levaya Shestakovka River, a suprapermafrost subaerial aquifer talik 180–200 m in width and more than 500 m in length was discovered by drilling. According to the results of geophysical studies, the talik has a complex spatial pattern with several water-conducting branches, and its thickness varies from 3 to 20 m [*Lebedeva et al., 2019*]. In landscape terms, it is confined to a flat area with a bearberry-lichen pine forest.

Thin (up to 3 m) water-bearing subaquatic taliks are distributed under bead-like widenings of the Levaya Shestakovka River channel. They are confined to areas where, due to the great depth of the river (up to 4 m), a layer of water remains under the ice in winter [*Tarbeeva et al., 2019*].

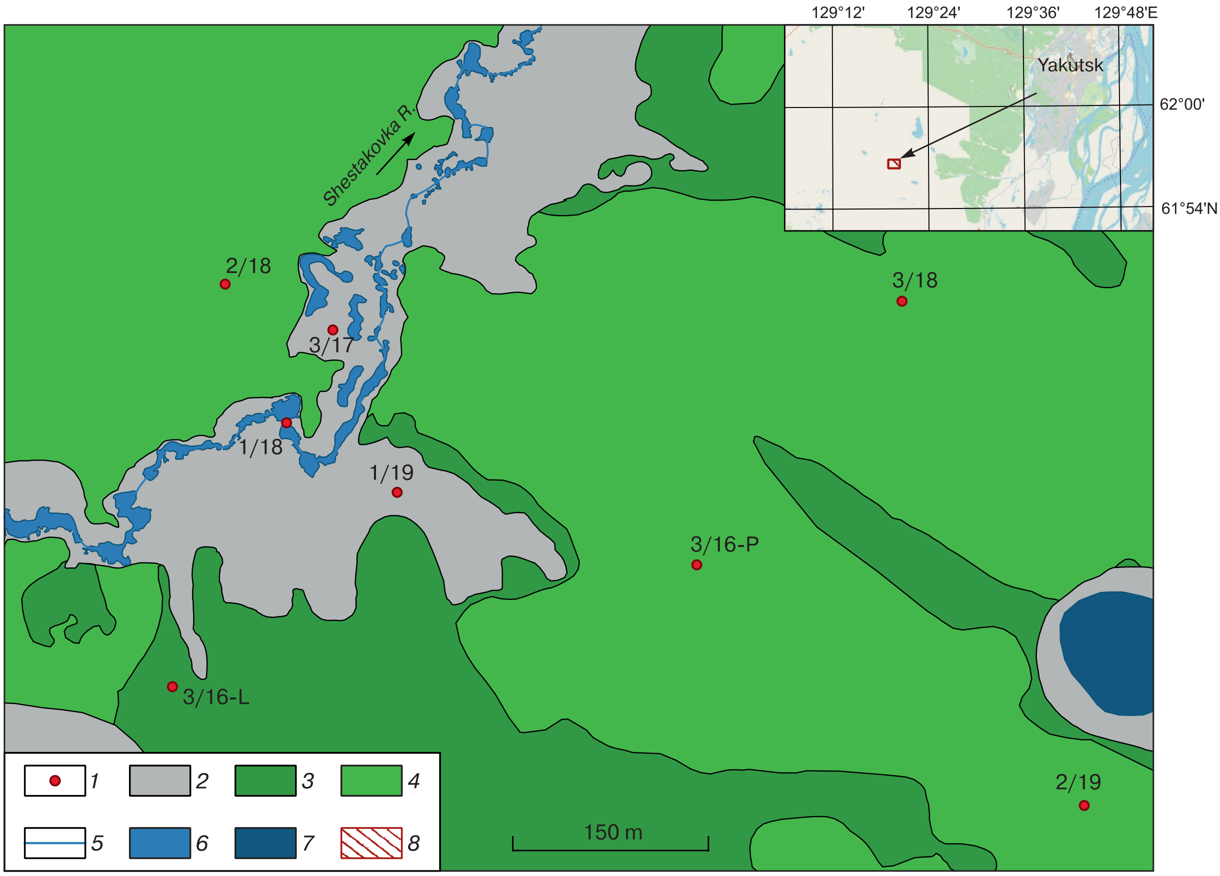

Fig. 1. Location of thermometric boreholes in the Levaya Shestakovka River basin:

1 – well, *2* – floodplain of the river and mire, *3* – larch forest, *4* – pine forest, *5* – river, *6* – widening of the river bed, *7* – lake, *8* – study area on the inset map.

RESEARCH METHODS

Drilling. Eight thermometric boreholes were drilled in different landscape and geomorphic conditions at the Levaya Shestakovka site in 2016–2019. Drilling works were carried out in April, when the layer of seasonal freezing reaches its maximum. Four boreholes were located under pine forests (Fig. 1; Table 1). The birch-larch forest, mire, flooded floodplain, and the Shestakovka River channel were characterized by one thermometric borehole each. Drilling was accompanied by core sampling to determine the moisture content of the rocks by the thermostatic-weight method. The texture of sediments from boreholes 3/16-P and 3/16-L was determined in the field; particle-size distribution of sediment samples from other boreholes was determined by the aerometric and sieve methods in laboratory conditions.

Monitoring of rock temperature within the Shestakovka River catchment. Six thermometric boreholes were equipped with temperature braids fitted with Maxim Integrated DL18B20 sensors. Temperature sensors were installed every 0.5 m up to a depth of 5 m and every meter in deeper layers (Table 1). Temperature measurement accuracy with DL18B20 thermistors is ±0.5°C. Readings were taken manually once a month. Two boreholes (3/16-P and 3/16-L) were equipped with Onset HOBO U12 temperature loggers. Recordings were made every three hours. The temperature measurement accuracy of Onset thermistors is ±0.25°C in the temperature range of 0–50°C and ±0.5°C at –20°C. As a rule, the thermistor error does not go beyond ±0.1°C [*Konstantinov et al., 2011*].

At the Onset HOBO weather station installed 2.5 km from the key site, the surface air temperature, the amount of liquid precipitation, and other basic meteorological parameters were recorded.

RESULTS

The structure of the upper part of the geological section in the key area. The main landscape units in the key area are represented by gentle slopes covered by pine forests, ravines and depressions with a predominance of larch forests and moss-herb mires, and the bottom of the Levaya Shestakovka River val-

Table 1. **Characteristics of temperature boreholes**

Bore-hole no.	Depth, m	Presence of talik	STL, m	SFL, m	Depth of zero annual amplitude, m	Soil composition	Location	Availability of data	Installed sensors
3/16-P	6	Yes	–	<3.0	<6	Fine and medium sand	Pine forest	Apr. 2016–Sep. 2019	Logger, 4 sensors at depths of 0.5, 1.0, 3.0, and 6.0 m
3/16-L	3	No	>1.0	–	*	Fine- and medium sand	Larch forest	Apr. 2016–Sep. 2019	Logger, 4 sensors at depths of 0.5, 1.0, 2.0, and 3.0 m
3/17	20	No	0.5–1.0	–	20	Peat, loam, loamy sand, sand	Flood-plain	Apr. 2017–Oct. 2020	26 sensors: every 0.5 m from 0 to 5 m and every meter from 5 to 20 m
1/18	12	No	2.5	–	15	Peat, sandy loam, fine and medium sand	Riverbed	Apr. 2018–Oct. 2020	18 sensors: every 0.5 m from 0 to 5 m and every meter from 5 to 12 m
2/18	15	No	4.5	–	5	Loam, sandy loam, fine and medium sand	Pine forest	Apr. 2018–Oct. 2020	21 sensors: every 0.5 m from 0 to 5 m and every meter from 5 to 15 m
3/18	11.6	Yes	–	3.0	10	Fine and medium sand	Pine forest	Apr. 2018–Oct. 2020	16 sensors: every 0.5 m from 0 to 5 m and every meter from 5 to 10 m
1/19	16.8	No	<1.0	–	>15	Peat, silt loam, sandy loam, fine and medium sand	Mire	Apr. 2019–Oct. 2020	21 sensors: every 0.5 m from 0 to 5 m and every meter from 5 to 15 m
2/19	21	Yes	–	3.0	>11.5	Medium- and coarse sand	Pine forest	Apr. 2019–Oct. 2020	17 sensors: every 0.5 m from 0 to 4.5 m and every meter from 4.5 to 11.5 m

Note: Dash – not applicable; asterisk – no data.

ley (floodplain and river channel). Absolute heights vary from 200–204 m asl on gentle slopes to 189–192 m asl on the floodplain and in the bottoms of ravines.

In areas with pine forests, the ground cover is sparse and consists of pine needle litter and separate thickets of lingonberry and bearberry. The geological section down to a depth of 21 m is represented by silty to coarse-grained sands (Fig. 2). Thus, on the right bank of the Levaya Shestakovka River, 640 m from its channel, on a very gentle slope (1°–2°), 21-m-deep borehole 2/19 penetrated medium-grained sands (4.9 m from the top) underlain by gray coarse-grained sands.

In borehole 3/16-P, 300 m from the edge of the floodplain, yellowish gray medium-grained sands with signs of ferrugination and few inclusions of organic matter were exposed throughout the section (to a depth of 10 m). Near the border of the pine and larch forests, according to the drilling data of borehole 3/18 with a depth of 11.6 m, the geological section is represented by fine-grained sands. In its upper part (up to a depth of 40 cm) sands are humified and contain inclusions of plant roots; to a depth of 2.2 m, they are ferruginous red and light gray; dove-gray sands lie beneath them, at the base of the section with inclusions of silt fraction and organic matter.

Boreholes 2/19, 3/16-P, and 3/18 encountered an aquifer at depths of 2.5–18.0, 1.7–7.2, and 2.2–7.7 m, respectively. The ice content of the SFL sands in April increased down the section from 1.5–2 to 8.3–10 wt.%, and it was 17.6–20 wt.% directly at the top of the aquifer. Permafrost immediately above the talik had the ice content from 18.3–19.6 to 33–35 wt.%.

On the left bank of the river in a pine forest, borehole 2/18 with a depth of 16.85 m revealed fine-grained sands. Light yellow sands with signs of ferrugination and rare inclusions of loam lie in the upper 2-m-thick layer. They are underlain to a depth of 7 m by fine- and very fine-grained silty light yellowish gray and bluish gray sands with horizons of ferrugination. Deeper, fine-grained gray sands with remains of organic matter, thin interlayers of greenish gray bluish sandy loams and silty loams with signs of ferrugination at depths of 11.1–13.5 m were exposed. The rocks throughout the section were frozen. Borehole 3/16-L, 3.9 m deep, uncovered uniform frozen gray and brown medium-grained sands with organic inclusions in the area of the birch-larch forest, The ice content of the permafrost ranged from 16.3 to 22.3 wt.%.

The geological structure of the low left-bank floodplain in the expansion of the river valley was described in detail by A.M. Tarbeeva [*2019*] according to drilling data from borehole 3/17 with a depth of 21 m. Fine- and medium-grained sands with interlayers of gravel and peat occur under the peaty litter from the surface to a depth of 4.7 m. They are underlain by silty sandy loams with peat interlayers. Beneath them, at the depth interval of 7.8–16.9 m, fine-grained sands with interlayers of plant remains are exposed. Silty sandy loams and silty sands occur at

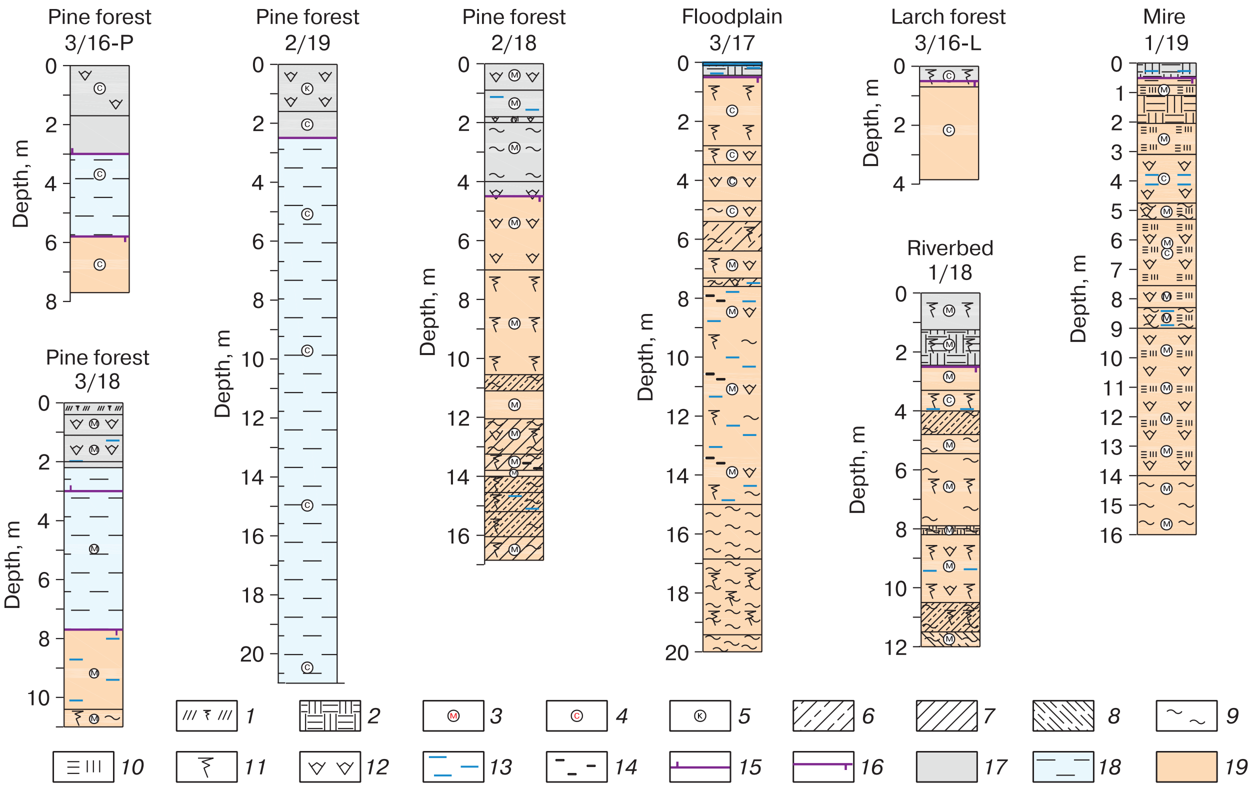

Fig. 2. Geological columns from boreholes in the upper reaches of the Shestakovka River basin:

1 – soil-vegetative layer, *2* – peat, *3* – fine sand, *4* – medium sand, *5* – coarse sand; *6* – loamy sand, *7* – loam, *8* – interlayering of loamy sand and loam, *9* – silt; *10* – peat admixture, *11* – organic residues, *12* – ferrugination, *13* – ice, *14* – charcoal, *15* – lower boundary of the seasonally frozen layer; *16* – permafrost table, *17* – active layer, *18* – water-bearing talik, *19* – permafrost.

the base of the section. The entire thickness was in the frozen state at the time of drilling. The ice content was maximum in the surface peaty horizon (>40%), varied from 17 to 35% at depths of 1–14 m, and decreased to 14–15% at depths of 18 and 20 m.

In borehole 1/18 under the river channel, gray, brown, and yellowish fine- and medium-grained sands with inclusions and thin interlayers of organic matter and peat were found in the surface (to a depth of 4 m) layer; below, to a depth of 4.8 m, there was a layer of silty bluish gray sandy loam with numerous ice lenses. At the depth interval of 4.8–10.5 m, silty fine-grained sands with organic interlayers and signs of ferrugination were exposed. They were underlain to a depth of 12 m by silty bluish gray sandy loams with interlayers of light loam and gray silty fine-grained sands. In April, the rocks throughout the section were in the frozen state. The ice content varied from 16 to 25.6 wt.% increasing at depths of 0.3–0.5 m (29.0–49.5 wt.%) and 4.0–4.5 m (31.0–59.4 wt.%).

The section under the mire on the right bank of the river was studied to a depth of 16 m in borehole 1/19. The upper 0.7-m-thick layer of ice-rich peat is underlain by interlayering ferruginous fine- and medium-grained sands with peat are exposed. The thickness of this layer is 3.1 m. Deeper, medium-grained bluish gray sands with ferruginous mottles and organic matter inclusions extend to a depth of 4.8 m; the layer of 4.8–5.3 m is represented by silty sand; the layer of 5.3–8.3 m, by fine- and medium-grained sands with interlayers of organic matter and ferrugination; in the lower part, they contain inclusions of loam and ice. Deeper, to the bottom of the well, fine-grained silty sands with interlayers of organic matter and ferrugination are exposed. Sediments of the entire section were in the frozen state.

Thus, according to the results of drilling on the right bank of the Levaya Shestakovka River performed in 2016–2019, the presence of water-bearing taliks was established in the areas of pine forest in sections with sandy sediments. In the analogous landscape positions on the left bank, sediments were frozen. Probable reasons for the absence of talik on the left bank are a finer texture of the sediments (the presence of fine-grained sands, loamy sands, loams, and silty sands) and a steeper slope ensuring more rapid runoff of surface and supra-permafrost waters into the river. Beyond the area of pine forests, talik zones were not found regardless of the composition of the sediments. Earlier, when studying subaerial taliks in the area of Malaya Chabyda Lake, 5 km from the study area, A.V. Boitsov established an important role of the intra-annual redistribution of moisture in sandy rocks of the aeration zone: the water content of thawed sand is always higher than that of frozen sand, which leads to the formation of a positive temperature shift at the bottom of the STL due to the difference in the thermal conductivity coefficients of sediments in the frozen and thawed states [*Boitsov, 2002*].

Temperature regime of rocks. The course of rock temperatures over time at depths of 3, 6, and 10 m is shown in Fig. 3; the thicknesses of the active layer (STL or SFL) and the depth of zero annual amplitudes are given in the Table 1.

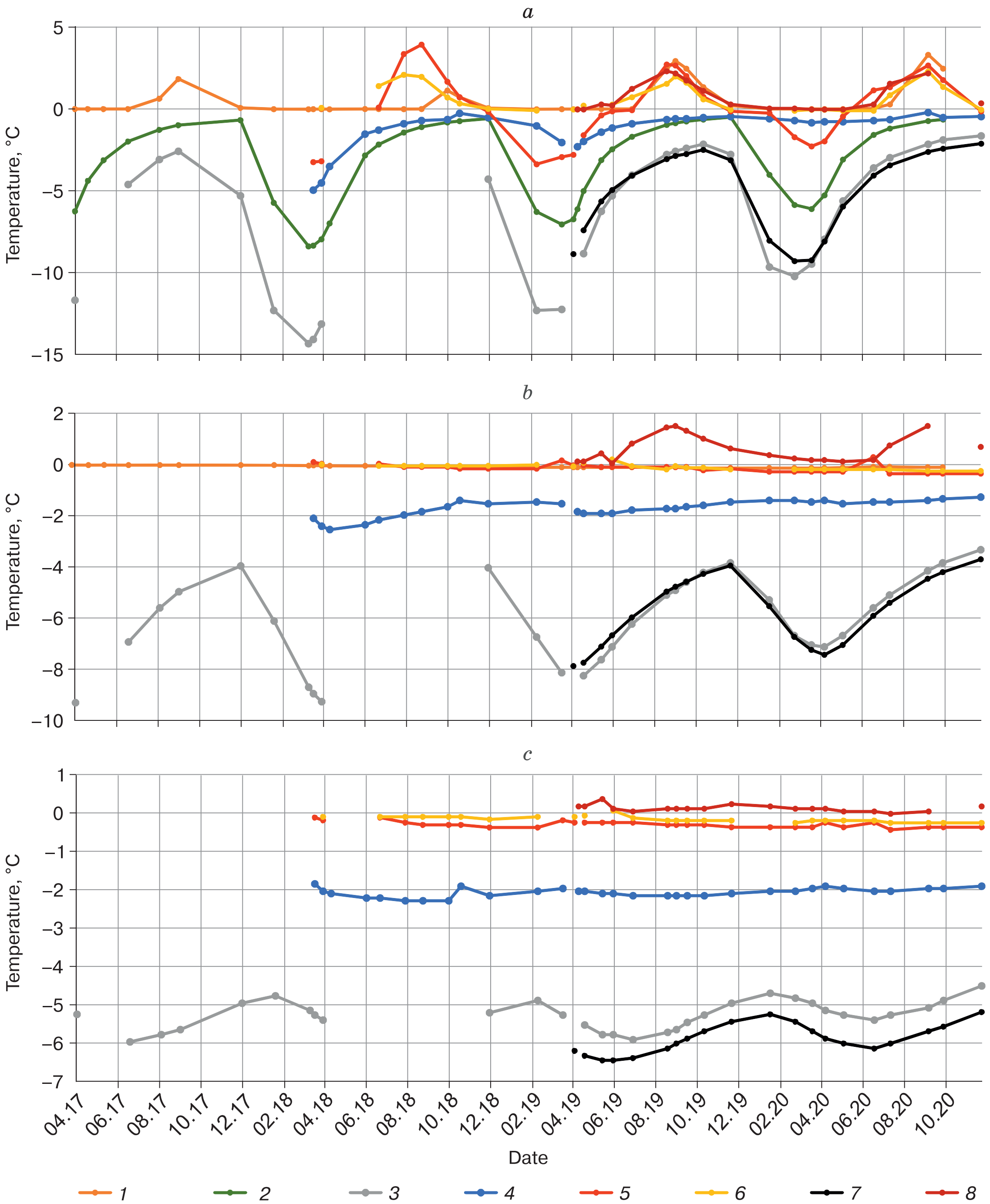

Fig. 3. Change in rock temperature at depths of (*a*) 3, (*b*) 6, and (*c*) 10 m from April 2017 to November 2020 in boreholes:

1 – 3/16-P, *2* – 3/16-L, *3* – 3/17, *4* – 1/18, *5* – 2/18, *6* – 3/18, *7* – 1/19, *8* – 2/19.

According to geothermal observations in borehole 3/17 on the river floodplain, the thickness of the STL does not exceed 1 m. At this depth, the temperature varies from −0.4°C in November–December to −18.6°C in February. The seasonally thawed layer begins to form in the late April–early May and completely freezes in October. At depths of 10 and 20 m, the temperature of the rocks varies from −4.7 to −6.0°C and from −3.6 to −3.9°C, respectively. The delay time of temperature fluctuations at a depth of 16–18 m (as compared with the surface) is 9–10 months. At a depth of 20 m, seasonal fluctuations are not fixed. In borehole 1/18 under the freezing narrow riverbed, thawing of rocks begins in the late April–early May, and they become fully frozen in November–December. The thickness of the STL is 2.5 m. At this depth, the temperature varies from 0 to −4.7°C; at a depth of 10 m, from −1.9 to −2.3°C; and at a depth of 12 m, from −2.1 to −2.5°C. The time of passage of the temperature wave from the surface to the depth of 10–12 m is about 10 months. The thickness of the layer of annual heat exchange is 15 m. There was a slight tendency towards an increase in the rock temperature at depths of 6–12 m over two years of measurements. Under the lake-like widenings of the river, where a layer of water over 2 m is preserved under the ice in winter, there are local taliks of up to 8 m in thickness under the channel [*Tarbeeva et al., 2019*]. The connection between under-channel and slope subaerial taliks, apparently, is absent in the winter season. This is evidenced by the merging of the surface freezing layer with permafrost on the floodplain of the Levaya Shestakovka River and under the mire at the footslope in October.

According to the results of geothermal measurements in borehole 1/19, the thickness of the STL under the mire is less than 1 m. At this depth, the temperature of the rocks varies from −0.7 to −12.4°C; at depths of 10 and 15 m it varies from −5.3 to −6.5°C and from −5.3 to − 5.6°C, respectively. Annual temperature fluctuations reach a depth of 15 m (the same depth as on the floodplain) with a lag of 9–10 months. The depth of the layer of zero annual amplitudes is 17–18 m.

According to the results of measurements in the larch forest (borehole 3/16-L), the thickness of the STL is slightly more than 1 m. At this depth, the rock temperature ranges from +0.2 to −11.3°C; at a depth of 3 m, from −0.6 to −8.4°C. The section is in the frozen state.

In borehole 2/18 on the left bank of the river valley in the pine forest, the STL thickness reaches the maximum: 4.5 m. At the depths of 5, 10, and 15 m, the temperature during the observation period varied within 0...−0.2, −0.3...−0.4 and −0.3...−0.5°C, respectively. From August 2018 to October 2020, soil cooling by 0.2–0.3°C was observed throughout the section. In warm and snowy winters after a wet summer, overwintering of thawed rocks is possible in this area.

Temperature regime of rocks in the area of suprapermafrost subaerial talik. In boreholes 3/18, 2/19, and 3/16-P, which exposed the suprapermafrost subaerial talik, the SFL thickness during the observation period was 2.0–3.5 m.

The maximum penetration depth of the isotherm −0.1°C was recorded in borehole 2/19, and the minimum one was recorded in borehole 3/16-P. In summer, the rocks at the base of the SFL warmed up to a temperature of 2.1–2.9°C. In the interval of occurrence of the water-bearing talik, the temperature of the rocks varied from 0°C in the winter months to 2.3°C in September–October. The permafrost underlying the talik had a high subzero temperature (−0.1... −0.3°C). The thickness of the layer of annual heat exchange is 6–12 m.

In general, in the areas of the suprapermafrost subaerial talik, the SFL thickness remained stable over the observation period; however, the timing of its formation and rock temperature extremes varied from year to year. Thus, according to the data obtained from borehole 3/16-P, the front of seasonal freezing reached a depth of 0.5 m in October 2016 and in November 2017–2020 (Fig. 4). Mean daily temperatures at this depth in winter usually did not fall below −14°C. Only the winter of 2017/18 was different, when the mean daily temperature of rocks at a depth of 0.5 m dropped to −17°C. As a result, in the subsequent summer season of 2018, the underlying

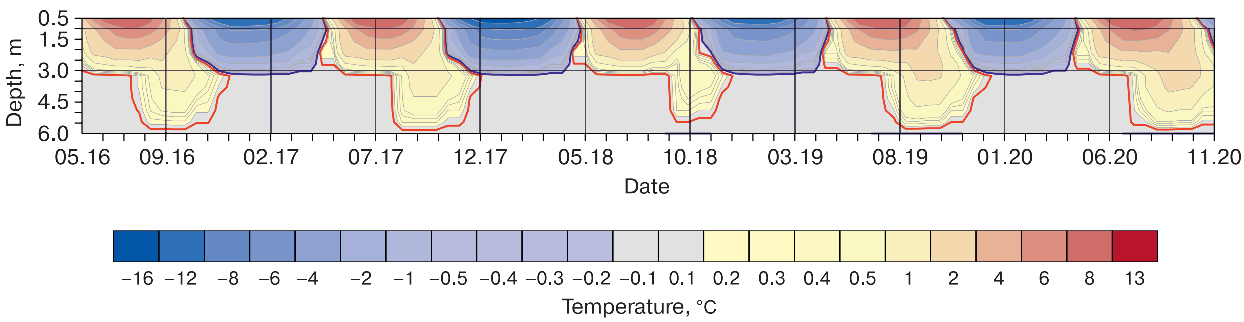

Fig. 4. Dynamics of rock temperature in borehole 3/16-P from May 2016 to November 2020.

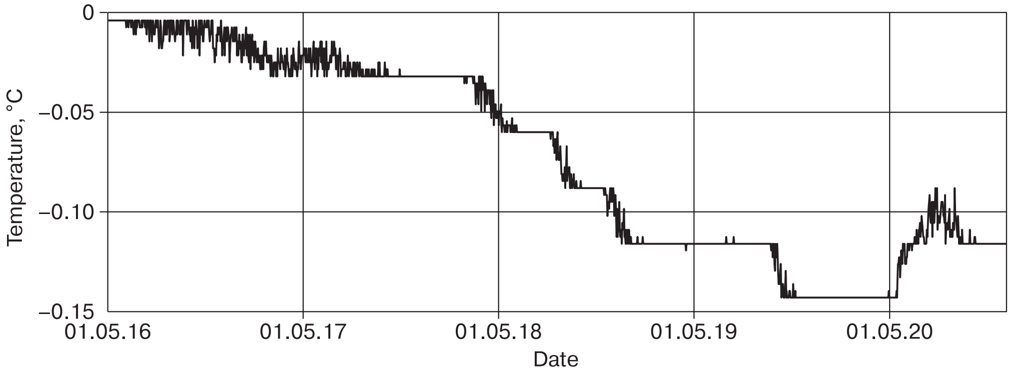

Fig. 5. Change in the mean daily temperature of rocks at a depth of 6 m in borehole 3/16-P.

thawed aquifers warmed up to a lower temperature and for a shorter time than in the previous years, but this effect was leveled in 2019–2020.

The thawing of SFL during the observation period began in mid-April and reached a depth of 0.5 m in May. Positive mean monthly temperatures of rocks in the aeration zone at a depth of 0.5 m were observed from May to September or October; at a depth of 1 m, from May to October; and at a depth of 3 m, from August to December in all years of observation, except for 2018, when the temperature was above 0°C only from October to December.

During the rest of the year, the temperature of rocks at a depth of 3 m was 0°C. At a depth of 6 m, from May 2016 to November 2020, gradual cooling of the rocks by 0.2°C took place (Fig. 5), and permafrost aggradation was observed; in 2020, rock temperature began to rise again.

DISCUSSION

The lowest values of rock temperature, low thickness of the STL (about 1 m), and a great depth of penetration of annual temperature fluctuations (>15 m) were observed in boreholes 3/17 and 1/19 on the floodplain and within the mire, respectively. Similar permafrost conditions were noted in the area of borehole 3/16-L in larch forest. In general, rock temperature patterns on the floodplain and under the mire were almost identical from the surface to a depth of 6–7 m. From a depth of 8 m, rock temperatures under the mire were 0.5–1.0°C lower than on the floodplain. In a depression occupied by larch forest, the temperature of the rocks was higher than that under the mire and on the floodplain: at a depth of 1 m, by 7–9°C in winter and by 0.2–0.5°C in summer; at a depth of 3 m, by 5–6°C in winter and by 1.5–2.0°C in summer. The low temperatures of the rocks in these landscapes were due to the presence of a wet organic (peat) horizon, the thermal conductivity of which is higher in winter than in summer. Thus, the thickness of ice-rich peat in the mire was 0.75 m, on the floodplain, 0.32 m; in the larch forest, a continuous moss cover of up to 0.3 m in thickness was developed on the surface.

In addition, at the end of autumn and at the beginning of winter, when the freezing of rocks begins and a snow cover forms, the discharge of suprapermafrost water on the surface was observed in the mire and on the floodplain. The resulting water-snow mass froze in the form of thin ice. In April 2017, in the area of borehole 3/17, the thickness of surface ice layer reached 8 cm. The presence of ice reduces the warming effect of the snow cover and favors deep and intense cooling of the rocks in winter. In the larch forest, snow cover accumulates throughout the cold season, which may explain the relatively high temperatures of the rocks there, especially in winter.

On gentle slopes under pine woodland with an almost absent ground cover, the thickness of the active layer reaches 4.5 m, and the depth of zero annual amplitude is 5–12 m. The geological section is represented here almost entirely by sandy sediments. Three boreholes exposed water-bearing taliks. Apparently, the warming of rocks is associated both with the absence of an organic horizon on the surface and with intensive filtration of suprapermafrost water of the STL and suprapermafrost groundwater in thawed sands with a high hydraulic conductivity. The temperature of water-saturated sands in the talik zone is about 0°C throughout the year; these sands do not freeze both because of the large costs of cold required to transform all liquid water into ice, and because of the continuous filtration of water through the pores and convective heat transfer. Probably, the thickness of the aeration zone and the depth of the aquifer table in the talik play an important role in the formation of the temperature regime. In boreholes 3/18 and 2/19 drilled in the upper part of the talik slope, seasonal temperature fluctuations penetrate to depths of 9–11 m, while in other boreholes of this group (3/16-P and 2/18), seasonal fluctuations decay at depths of 5–6 m. This can be explained by a shallower depth of suprapermafrost water in the upper part of the slope.

An intermediate position between "warm" and "cold" sites is occupied by the riverbed. The thickness of the STL here is 2.5 m, and the depth of zero annual amplitude is about 15 m. Apparently, river flow from May to October and the absence of an organic horizon contribute to higher temperatures in the section compared to those within the floodplain and mire. At the same time, loamy sands and loams present in the section limit groundwater filtration, convective heat transfer, and the formation of thawed horizons. As a rule, the rocks that have thawed during the warm period are completely frozen by February–March. As shown in Fig. 6, rock temperature in borehole 3/16-P at a depth of 6 m slightly decreased from zero values in 2016 to –0.1°C in 2020. A weakly pronounced tendency to temperature decrease at depths of 10–20 m is also characteristic of "warm" sites in the talik area (boreholes 3/18 and 2/19) and beyond it (borehole 2/18). The length of the series of observations is insufficient to draw definite conclusions about the trend of temperature changes; however, the consistency of the noted changes over 2–4 years for four boreholes allows us to conclude that in these years the permafrost table somewhat ascended. At the "cold" sites, multidirectional trends were observed. Under the river channel (borehole 1/18) and on the river floodplain (borehole 3/17), a slight decrease in rock temperature by 0.1–0.3°C took place, whereas linear approximation for the mire site attests to some rise in the permafrost temperature over the past year and a half. The absence of a pronounced increase in permafrost temperature is consistent with the results of the analysis of long-term (39 years) geothermal observations in the area of research by S.P. Varlamov [*Varlamov et al., 2021*], who came to the conclusion that the thermal state of the permafrost remains stable, regardless of the type of terrain and the nature of the deposits.

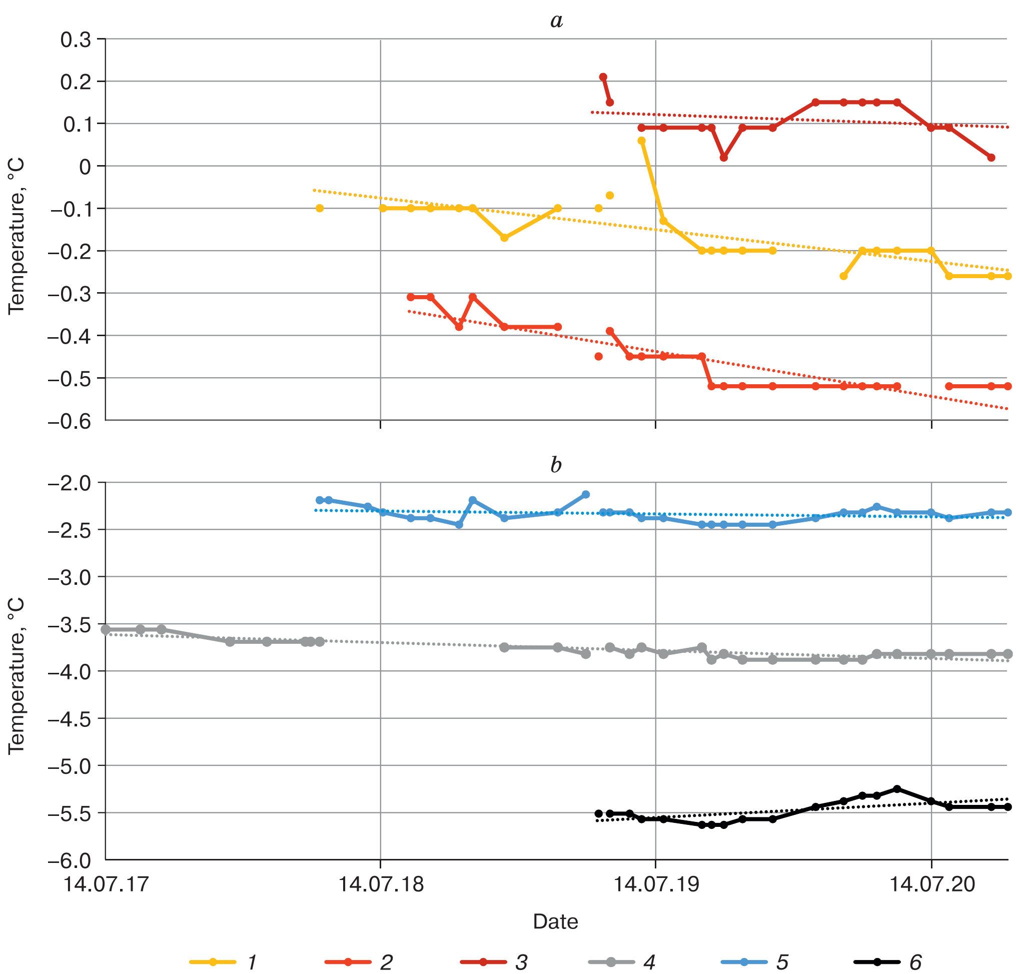

Fig. 6. Change in rock temperature at depths of 10–20 m in boreholes and linear approximation trend:

a: *1* – borehole 3/18, 10 m; *2* – borehole 2/18, 15 m; *3* – borehole 2/19, 12 m; *b*: *4* – borehole 3/17, 20 m; *5* – borehole 1/18, 12 m; *6* – borehole 1/19, 15 m.

CONCLUSIONS

In the key area of about 1 km^2 in the Levaya Shestakovka River basin, geothermal conditions are different under the same meteorological background. The depth of permafrost table varies from 0.5 to 20 m. Both seasonally frozen and seasonally thawed conditions are observed in the upper part of the geological section depending on the composition and properties of the sediments. The highest rock temperatures are characteristic of the area of aquiferous suprapermafrost taliks confined to gentle slopes composed of sandy sediments and covered with sparse pine forests. In such areas, the thickness of the seasonally frozen layer reaches 3 m, and the depth of zero annual amplitude varies from 6 to 12 m. The thawed rocks are preserved due to the constant filtration of groundwater in them. The presence of sediments with lower infiltration capacity (loamy sands and loams) in the upper part of the section does not favor the formation of talik zones.

The lowest rock temperatures are characteristic of the mire site and the floodplain. The thickness of the seasonally thawed layer varies from 0.5 to 1.0 m, and the depth of zero annual amplitudes exceeds 15 m. The formation of the low-temperature sediments is facilitated by the presence of an organic horizon in the upper part of the section and by the small snow depth because of the formation of icings.

In the period from 2016 (2018) to 2020, slow freezing of the taliks from below was noted due to a weakly pronounced cooling of the strata underlying the thawed aquifers. Beyond the areas of taliks, weak multidirectional changes in rock temperature were recorded.

The established wide distribution of suprapermafrost subaerial taliks in a small area of research within the continuous permafrost zone suggests the possibility of their existence in similar landscape-permafrost conditions in Central Yakutia.

Acknowledgments. *Rock temperature monitoring was carried out with the financial support of the Russian Foundation for Basic Research (project 20-05-00670). Borehole drilling and study of the geological section was carried out within the framework of state assignment 122012400106-7 "Cryolithozone groundwater: patterns of formation and regime, features of interaction with surface water and frozen rocks, prospects for use".*

References

Anisimova N.P. (ed.), 2003. *Groundwaters in Central Yakutia and Prospects of Their Use*. Novosibirsk, Acad. Publ. Geo, 117 p. (in Russian).

Anisimova N.P., Pavlova N.A., 2014. *Hydrogeochemical Studies of Permafrost in Central Yakutia*. Novosibirsk, Acad. Publ. Geo, 198 p. (in Russian).

Anisimova N.P., Pavlova N.A., Stambovskaya Ya.V., 2005. The chemical composition of the water of valley taliks in the middle reaches of the Lena River. *Nauka i obrazovanie* **4** (40), 92–96.

Biskaborn B.K., Smith S.L., Noetzli J. et al., 2019. Permafrost is warming at a global scale. *Nat. Commun.* 10, p. 264. doi: 10.1038/s41467-018-08240-4.

Boike J., Nitzbon J., Anders K. et al., 2019. A 16-year record (2002–2017) of permafrost, active-layer, and meteorological conditions at the Samoylov Island Arctic permafrost research site, Lena River delta, northern Siberia: an opportunity to validate remote-sensing data and land surface, snow, and permafrost models. *Earth Syst. Sci. Data* **11**, 261–299. doi: 10.5194/essd-11-261-2019.

Boitsov A.V., 1985. Conditions of formation and the regime of slope taliks in Central Yakutia. In: *Hydrogeological Studies*. Yakutsk, Izd. Melnikov Permafrost Inst. SB RAS, p. 44–55 (in Russian).

Boitsov A.V., 2002. The Conditions of Formation and the Regime of Groundwater in Suprapermafrost and Intrapermafrost Runoff in Central Yakutia. Cand. Sci. (Geol.) Diss., Yakutsk, 176 p. (in Russian).

Bulygina O.N., Razuvaev V.N., Korshunova N.N., Shvets N.V., 2022a. Description of the Data Array of Monthly Precipitation at Weather Stations of Russia: Certificate of State Registration of the Database No. 2015620394. http://meteo.ru/data/158-total-precipitation#opisanie-massiva-dannykh (last visited: March 15, 2022).

Bulygina O.N., Razuvaev V.N., Trofimenko L.T., Shvets N.V., 2022b. Description of the Data Array of the Mean Monthly Air Temperature at Weather Stations of Russia: Certificate of State Registration of Database No. 2014621485. http://meteo.ru/data/156-temperature#opisanie-massiva-dannykh (last visited: March 15, 2022).

Fedorov A.N., Ivanova R.N., Park H. et al., 2014. Recent air temperature changes in the permafrost landscapes of northeastern Eurasia. *Polar Sci.* **8** (2), 114–128. doi: 10.1016/j.polar.2014.02.001.

Fedorov-Davydov D.G., Davydov S.P., Davydova A.I. et al., 2018. The temperature regime of soils in the Northern Yakutia. *Earth's Cryosphere* XXII (4), 12–19.

Gagarin L.A., Semernya A.A., Lebedeva L.S., 2016. Assessment of thermosuffosion processes in Central Yakutia on the example of the Ulakhan-Taryn site. *Inzhenern. Geol. Gidrogeol. Geokriol.* 3, 252–262.

Galanin A.A., 2015. Cryogenic-eolian mechanism of formation of aquiferous interpermafrost taliks in Central Yakutia. In: *Proc. XXI Conf. on Groundwater in Siberia and the Far East*. Yakutsk, Izd. Melnikov Permafrost Inst. SB RAS, p. 80–84 (in Russian).

Gorokhov A.N., Fedorov A.N., 2018. Current trends of climate change in Yakutia. *Geograf. Prirodn. Res.* 2, 111–119.

Kaverin D.A., Pastukhov A.V., Novakovskiy A.B. et al., 2019. Landscape and climatic factors impacting the thaw depth in soils of permafrost peat plateaus (on the example of CALM R52 site). *Earth's Cryosphere* XXIII (2), 53–60.

Konishchev V.N., 2009. Response of permafrost to climate warming. *Byull. Mosk. Gos. Univ. Ser. 5: Geogr.* 4, 10–20.

Konstantinov P.Ya., Fedorov A.N., Machimura T., Iwahana G., Yabuki H., Iijima Y., Costard F., 2011. Use of automated recorders (data loggers) in permafrost temperature monitoring. *Kriosfera Zemli* XV (1), 23–32.

Lebedeva L.S., Bazhin K.I., Khristoforov I.I. et al., 2019. Suprapermafrost subaerial taliks, Central Yakutia, the Shestakovka River basin. *Earth's Cryosphere* XXIII (1), 35–44.

Lytkin V.M., Galanin A.A., Shaposhnikov G.I. et al., 2018. Temperature regime of dune massifs in Central Yakutia. In: *Geo-*

logy and Mineral Resources of the Northeast of Russia (Proc. VIII All-Russia Sci.-Pract. Conf.). Yakutsk, Izd. Melnikov Permafrost Inst., vol. 2, 237–240 (in Russian).

Moskalenko N.G., 1998. Investigation of the seasonal thaw of peatlands in the West Siberian cryolithozone. *Kriosfera Zemli* II (1), 32–35.

Neradovskii L.G., 2020. Changes in the background permafrost temperature in Yakutsk during current period of climate warming in Siberia (1976–2011). *Earth's Cryosphere* XXIV (4), 40–49.

Oberman N.G., Lygin A.M., 2009. Forecasting the degradation of permafrost on the example of the Northeast of European Russia. *Razvedka i Okhrana Nedr* 7, 15–20.

Pavlov A.V., 1979. *Thermal Physics of Landscapes*. Novosibirsk, Nauka, 284 p. (in Russian).

Pavlov A.V., Anan'eva G.V., Drozdov D.S. et al., 2002. Monitoring of active layer and the temperature of frozen grounds in the North of Russia. *Kriosfera Zemli* VI (4), 30–39.

Ponomareva O.E., 1999. Aquiferous taliks in sandy sediments on the lower reaches of the Vilyui River. *Kriosfera Zemli* III (4), 84–89.

Semernya A.A., Gagarin L.A., Bazhin K.I., 2018. Cryohydrogeological features of the site of intrapermafrost aquifer distribution in the Eruu Spring area (Central Yakutia). *Earth's Cryosphere* XXII (2), 26–34.

Shepelev V.V., 2011. *Suprapermafrost Waters in the Cryolithozone*. Novosibirsk, Acad. Publ. Geo, 169 p. (in Russian).

Shepelev V.V., Boytsov A.V., Oberman N.G. et al., 2002. *Groundwater Monitoring in Permafrost*. Yakutsk, Izd. Melnikov Permafrost Inst. SB RAS, 172 p. (in Russian).

Skryabin P.N., Skachkov Yu.B., Varlamov S.P., 1999. Climate warming and thermal state of ground in Central Yakutia. *Kriosfera Zemli* III (3), 32–40.

Tarbeeva A.M., Lebedeva L.S., Efremov V.S. et al., 2019. Conditions and processes of formation of a beaded channel of a small river in permafrost, Shestakovka River (Central Yakutia). *Earth's Cryosphere* XXIII (2), 33–44.

Varlamov S.P., Skachkov Y.B., Skryabin P.N., 2020. Influence of climate change on the thermal condition of Yakutia's permafrost landscapes (Chabyda station). *Land* **9** (5), p. 132. doi: 10.3390/land9050132.

Varlamov S.P., Skachkov Yu.B., Skryabin P.N., 2021. *Monitoring of the Thermal Regime of Soils in Central Yakutia*. Yakutsk, Izd. Melnikov Permafrost Inst. SB RAS, 156 p. (in Russian).

Varlamov S.P., Skryabin P.N., 2012. Dynamics of the thermal state of soils in permafrost landscapes of Central Yakutia. *Izvest. Samarsk. Nauchn. Tsentra RAN* 14 (1–8), 2040–2044.

Vasiliev A.A., Gravis A.G., Gubarkov A.A. et al., 2020. Permafrost degradation: results of long-term geocryological monitoring in the Western sector of the Russian Arctic. *Earth's Cryosphere* XXIV (2), 14–26.

Zabolotnik S.I., Zabolotnik P.S., 2014. Conditions of ground seasonal thawing and freezing in South Yakutia. *Kriosfera Zemli* XVIII (1), 23–30.

Received May 6, 2022
Revised December 11, 2022
Accepted February 1, 2023

Translated by A.V. Muravyev