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TEMPERATURE CHANGES IN PERMAFROST AND GLACIER ICE IN THE HIGH-MOUNTAIN PART OF THE SUNTAR-KHAYATA RIDGE (NORTHEASTERN RUSSIA) FOR THE PERIOD 1957–2017

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In 1957–1959, according to the program of the 3rd International Geophysical Year, the temperature of rocks (to a depth of 20 m) and glacier ice (to a depth of 45 m) was measured in the area of a high-mountain weather station (glacier No. 31) in the central part pf the Suntar-Khayata Ridge (northeastern Russia). In 2012–2017, the Russian–Japanese expedition carried out new measurements of the temperature of rocks and glacier ice at the same places. A comparison of the data on the mean monthly temperatures of glacier ice at a depth of 10 m in 1958 and 2012 attests to their rise by 1.0–1.6°C. As there was no possibility to perform direct measurements of rock temperature at a depth of 20 m in 2012–2017, we used an indirect method to estimate it at the depth of zero annual amplitude. According to our estimate, in the past 60 years, it could have increased by up to 1.6°C. Regime studies of the dynamics of seasonal thawing were carried out at four experimental plots; of the dynamics of freezing of the seasonally thawed layer, at one plot.

Keywords: *climate change, permafrost, glaciers, ground temperature, seasonal thaw, seasonal freezing.*

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INTRODUCTION

As part of the scientific program of the 3rd International Geophysical Year (IGY), in 1957–1959, comprehensive studies of the high-mountain part of the Suntar-Khayata Ridge (northeastern Russia) were organized. They were carried out by the V.A. Obruchev Institute of Permafrost Science of the USSR Academy of Sciences together with the Kolyma Branch of the USSR Hydrometeorological Service. A weather station was built and put into operation specifically for this project at an altitude of 2070 m a.s.l. Glaciological, geomorphological, meteorological, and geobotanical studies were performed. The results of these works were summarized in two monographs and two collections [*Koreysha, 1963a,b; Sapozhnikov, 1963; Grave et al., 1964*]. The scientific program also included work on studying the thermal regime of mountain permafrost and glacial ice [*Grave, 1962*]. Between 1960 and 2010, this region continued to be studied by glaciologists mainly on the basis of remote sensing methods with short-term field reconnaissance work. They showed a tendency for long-term degradation of glaciers of the Suntar-Khayata Ridge, which has significantly intensified over the past 30 years [*Vinogradov et al., 1972; Yamada et al., 2002; Ananicheva et al., 2003, 2006; Takahashi et al., 2011*]. From 1945 to 2003, the area of glaciation decreased by approximately 20% [*Ananicheva et al., 2006*].

A Russian–Japanese scientific expedition worked there in 2012–2014. The P.I. Melnikov Permafrost Institute of the Siberian Branch of the Russian Academy of Sciences (RAS), Institute of Geography RAS, Japan Agency for Marine and Earth Sciences and Technology, Polar Research Institute (Japan), Kitami Institute of Technology (Japan), and Chiba University (Japan) participated in this work. The results of glaciological, geomorphological, and biological studies of this expedition were presented in a number of publications [*Galanin et al., 2013, 2014; Melnikov et al., 2013; Nakazawa et al., 2015; Mavlyudov, Ananicheva, 2016; Shirakawa et al., 2016; Zhang et al., 2017*]. This paper presents the results of observations of the thermal state of frozen rocks and glacial ice in the high-mountain part of the Suntar-Khayata Ridge carried out by members of the Russian–Japanese expedition 55–60 years after works under the 3rd IGY program.

STUDY AREA

The Suntar-Khayata Ridge is located in the northeast of Russia. It is a continuation of the Verkhoyansk mountain system and extends for 450 km from the upper reaches of the Tompo River to the upper reaches of the Ini River. The ridge is the divide of the large Aldan and Indigirka rivers of the Arctic basin and the rivers of the Sea of Okhotsk basin. Its northern part to the middle reaches of the Suntar River has a submeridional direction and is elevated up to 2200 m a.s.l. The central, most elevated part of the ridge stretches from northwest to southeast and rises above 2900 m a.s.l. In the southern part, the ridge has a sublatitudinal direction, and its heights decrease to 1900 m a.s.l. The mountain system is composed mainly of Permian and Triassic rocks (the Verkhoyansk complex). They are represented by interlayering shales, sandstones, siltstones, and mudstones. Granitoid dikes occur in the high mountain ranges. The rocks of the Verkhoyansk complex are unconformably overlain by Cretaceous volcanic strata – tuffs, rhyolites, and porphyries.

Modern glaciation takes place in the central, highest part of the ridge. As of 2006, there were 195 glaciers with a total area of 163 km^2 [*Ananicheva et al., 2006*]. Modern glaciers of the Suntar-Khayata Ridge occupy both ancient glacial forms and those created in the Holocene. There are cirque, valley, and hanging glaciers. High-mountain regions have a harsh Arctic desert climate, but they are more humid compared to the Arctic plains. The cold period of the year lasts nine months. At heights above 2000 m a.s.l., the mean January temperature is –27°C. Strong winds blow here and snowstorms are common. Northwestern winds predominate. The snow cover depth in the mountains is 50–90 cm, increasing to several meters in places of snowdrifts. Summer in the mountains is cool and lasts from mid-June to the end of August. The mean July temperature is +7°C. There is no frost-free period. The summer period is characterized by significant cloudiness. Annual precipitation on the main watershed is up to 1000 mm. The amount of precipitation in summer is significantly higher than in winter. Continuous permafrost with mean annual rock temperatures of –5 to –13°C is developed. The thickness of frozen rocks was measured instrumentally in the western, lower part of the ridge, where it reaches 380–420 m [*Balobaev, Levchenko, 1978*].

DESCRIPTION OF EXPERIMENTAL SITES AND RESEARCH METHODS

A weather station that operated in 1957–1959 according to the program of the 3rd IGY (hereinafter referred to as the IGY weather station) (Fig. 1) is located on a mountain range pass between the valleys of the Suntar and Burgali rivers (62°37′28″ N, 140°48′20″ E). The absolute height of the weather station site is 2070 m. The surface is covered with coarse blocky-gravelly clastic material. There is no vegetation cover, except for crustose lichens. According to drilling data, coarse blocky-gravelly and loamy gravelly deposits with ice interlayers are developed in the area under consideration to a depth of 9.6 m. In the depth range of 9.6–15.3 m, there are fractured siliceous mudstones underlain by strong siliceous mudstones. The thickness of the seasonally thawed layer (STL) is 1.0–1.2 m.

In 1957, 3 boreholes were drilled to the depths of 1, 5, and 20 m, in which metal resistance thermometers were installed on cables. After their installation, the boreholes were not filled with soil. Measurements to a depth of 1 m were carried out four times a day; in the depth range of 1.5–5 m, once a day; and in the depth range of 7.5–20 m, once every 5 days. Observa-

Fig. 1. IGY weather station. Glacier No. 31 is in the background.

tions of rock temperature were carried out from 1957 to 1959. During this period, air temperature measurements were also taken several times a day. Air temperature measurements were continued in 1961–1963. To determine the temperature of ice in the middle part of glacier No. 31, in the summer of 1958, a 45-m-deep borehole was drilled, in which a wired measuring set based on thermistors was frozen. Temperature measurements in this borehole were carried out up to the end of December 1958.

In 2012, the Russian–Japanese expedition selected four sites on different landforms to observe the thermal regime of rocks (Table 1, Figs. 2 and 3).

Site 1 is located on the territory of the IGY weather station near old temperature boreholes. The site description is given above.

Site 2 is located on the surface of the strath terrace of the Burgali River at a distance of 50 m from the river channel. The surface of the terrace in this area is relatively flat. The upper 1.5-meter thickness is composed of gravel sediments with inclusions of sand and boulders.

Site 3 was selected on a small saddle in the lower part of a mountain slope of western exposure. Its dimensions are 10 × 5 m. Down to a depth of 1.2 m, there are loamy sands and sands of a brownish yellow color with inclusions of small gravels.

Site 4 is located on the top of the terminal moraine ridge. The moraine is composed of boulder-gravel strata, the relative height of which is 8–10 m. The surface of the moraine is uneven, representing an alternation of swells and depressions. The vegetation cover at all the sites is virtually absent, except for crustose lichens.

Four-channel temperature loggers HOBO U12-008 with TMC-HD temperature sensors were used as measuring instruments at all the sites. Before the start of field work, all recorders and sensors underwent a control check of temperature readings in laboratory conditions with the determination of the necessary corrections. Since the expedition did not have a drilling rig for drilling rocks, the installation of temperature sensors was carried out by digging pits. Information on the installation depth of the sensors is given in Table 1. After installing wired sets of temperature sensors, the pits were completely filled with previously extracted rock. For the best comparison with soil temperature data obtained in 1957–1959, site 1 was chosen in close proximity to the old temperature boreholes of the IGY weather station.

During a reconnaissance survey on the surface of glacier No. 31, an old wired thermal measuring set was found, which over 55 years ended up on the surface of the glacier as a result of its melting. Having data on the speed of glacier movement obtained during the work of the IGY expedition, a place was chosen to install temperature sensors into the glacier ice 200 m higher along the centerline of the glacier, approximately corresponding to the location of the borehole in 1957–1959. Here, using a portable steam generator unit, a 10-m-deep borehole was drilled, in which TMC-HD temperature sensors were installed at depths of 1, 3, 5 and 10 m (Table 1, Fig. 2). A second temperature 10-m-deep borehole was set up in the upper part of glacier No. 31.

In our studies, the mean annual temperature of rocks at different depths (t_{ma}) is determined not for the calendar year, but for the calculation year proposed by A.V. Pavlov [*1965*]. The beginning of the annual period is taken to be the average long-term date of the beginning of winter freezing of rocks, which coincides in time with the transition of soil surface temperature to stable subzero values. In this case, the entire cold period turns out to be within one year. This approach to choosing the boundaries of the annual period for calculating t_{ma} is more correct for the permafrost region, where the thermal regime of the soil is determined by the conditions of the cold period rather than the warm one. In our studies, September 1 is taken as the beginning of the annual calculation period. To designate it, a double designation scheme is used. For example, designation 2012/13 means that the considered year begins on September 1, 2012 and ends on August 31, 2013. The values of the mean annual air temperature were also determined for the calculated annual periods.

Table 1. **Experimental sites**

Site number	Geomorphic position	Altitude, m a.s.l.	Rock composition	Maximum thickness of STL, m	Depth of sensors, m	Data collection period
1	Mountain pass	2070	Crushed stone, debris, blocks	1.10–1.20	0.0, 0.6, 0.8, 1.2	August 2012–August 2017
2	Erosion terrace of the Burgali River	1982	Pebbles, gravel, sand	1.30–1.40	0.0, 0.4, 0.8, 1.2	August 2012–August 2017
3	Small saddle on a mountain slope	2075	Loamy sand, sand, debris	1.00–1.05	0.0, 0.4, 0.8, 1.2	August 2012–August 2017
4	Moraine ridge	2022	Pebbles, gravel, boulders	1.30–1.40	0.0, 0.4, 0.8, 1.2	August 2012–August 2017
5	Middle part of glacier No. 31	2248	Glacial ice	–	1.0, 3.0, 5.0, 10.0	August 2012–August 2015
6	Upper part of glacier No. 31	2443	Glacial ice	–	1.0, 3.0, 5.0, 10.0	August 2012–August 2015

Fig. 2. General view of the experimental sites.

a – site 1 (IGY weather station); *b* – site 2 (strath terrace of the Burgali River); *c* – site 3 (small saddle on a mountain slope); *d* – site 4 (moraine ridge); *e* – site 5 (middle part of glacier No. 31); and *f* – site 6 (upper part of glacier No. 31).

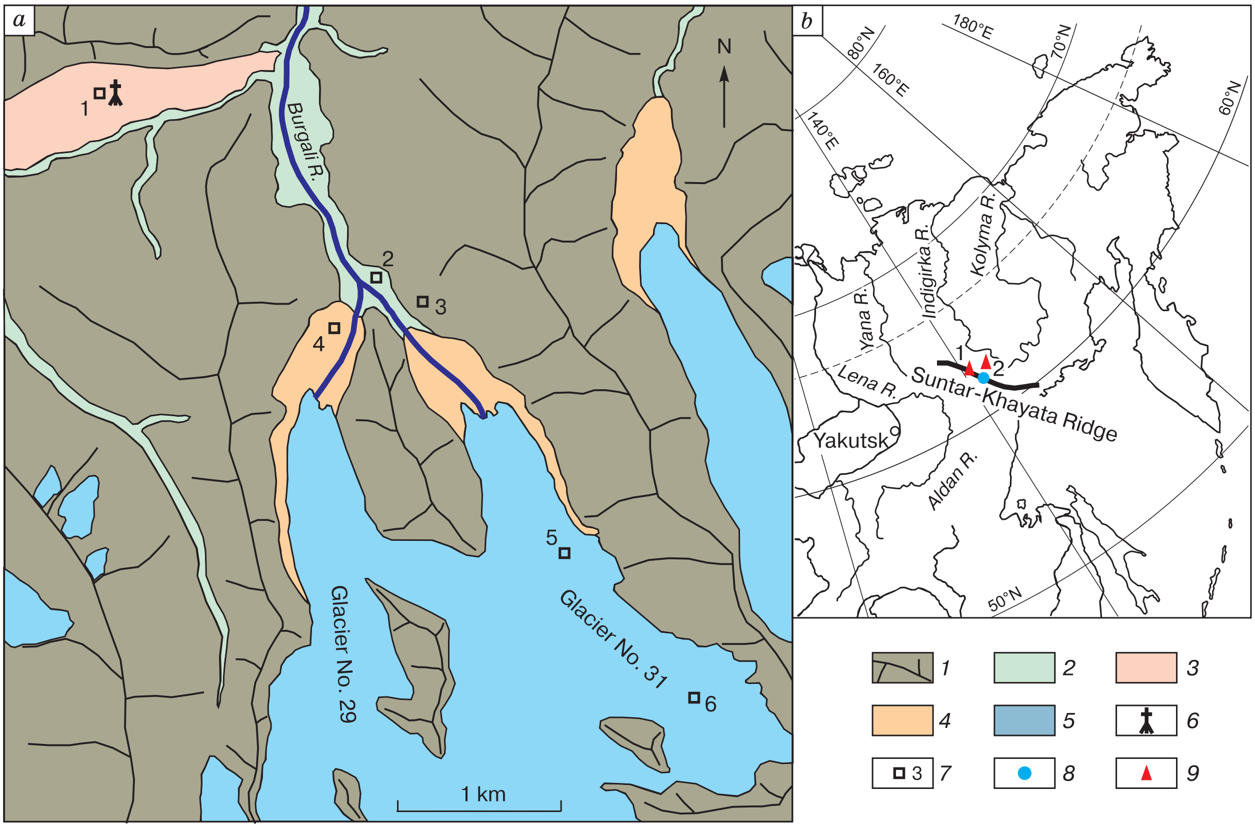

Fig. 3. Schematic map of the research area.

a: 1 – ridge lines; *2* – valley bottoms; *3* – mountain pass; *4* – moraine ridges; *5* – glaciers; *6* – IGY weather station; *7* – experimental site and its number; *b: 8* – research area; *9* – weather stations on a small-scale diagram (1, Vostochnaya (East); 2, Agayakan).

RESULTS AND DISCUSSION

Data from weather stations indicate significant warming in the study region over the past 60 years. Figure 4 shows graphs of changes in the mean annual air temperature from 1955 to 2020 according to data from the two weather stations closest to the research site: Agayakan (63°20′07″ N, 141°43′56″ E, 777 m a.s.l.) and Vostochnaya (63°14′27″ N, 139°37′53″ E, 1286 m a.s.l.). The trends in air temperature increase were 0.38°C/10 years for the Agayakan weather station and 0.25°C/10 years for the Vostochnaya weather station. As can be seen, the warming during the period under review was stronger in the area with a lower absolute height. In the high-mountainous part of the Suntar-Khayata Ridge, the air temperature regime was studied during the operation of the IGY weather station (1957–1959 and 1961–1963) and the Russian-Japanese expedition (2012–2014). Unfortunately, in recent years, due to technical reasons, it has been possible to obtain such data only for one annual period. Figure 5 shows the mean annual air temperature at the site of the high-mountain weather station for different years. Its lowest value was noted in 1958 (–14.9°C), and the highest – in 2012 (–12.1°C). Table 2 shows a comparison of the mean annual air temperature at the IGY weather station with lower-lying weather stations. The closeness of the air temperature values at the IGY weather station with the Vostochnaya weather station is clearly seen. This suggests that above the absolute level of 1286 m, the air temperature remains almost unchanged.

Data on the mean annual rock temperature were obtained by the authors at 4 sites for five annual calculation periods from 2012/13 to 2016/17. Figure 6 shows fluctuations of t_{ma} at a depth of 1.2 m over the indicated period. As can be seen from the graphs, lower temperatures (–7.2...–9.0°C) are characteristic of the moraine ridge (site 4) and the small saddle on the slope (–7.1...–8.7°C) (site 3), and higher ones – for the strath terrace of the Burgali River (–5.5...–7.1°C) (site 2) and mountain pass (–7.2...–7.8°C) (site 1). The smallest interannual variations in t_{ma} at a depth of 1.2 m for the entire period of observations were noted at the mountain pass (0.6°C), which is apparently due to the annual presence of snow blows here.

The maximum thickness of the STL determined from temperature data at all the sites for the entire observation period was within the range of 1.0–1.4 m

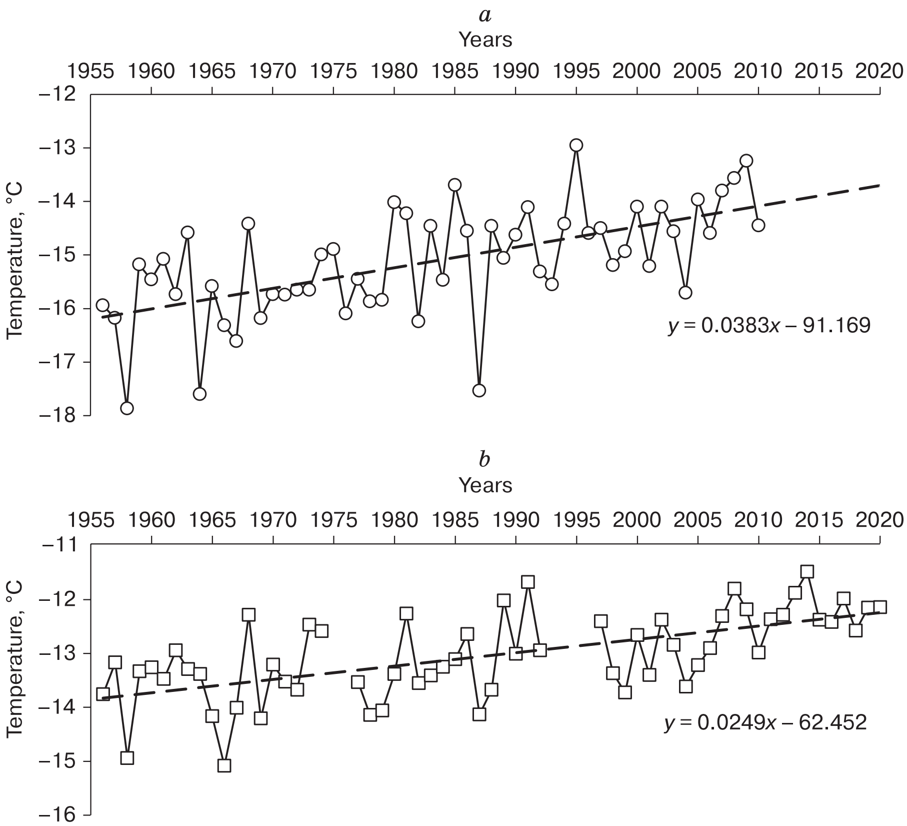

Fig. 4. Changes in the mean annual air temperature in 1955–2020 according to records at weather stations (*a*) Agayakan and (*b*) Vostochnaya.

(Table 1). The minimum thawing was observed at site 3, where the STL is composed of fine sediments. The beginning of the thawing greatly depends on the position of the site in the relief, on which the time of melting of the snow cover depends. As can be seen from the data in Table 3, the earliest dates of the onset of thawing (May 30–June 13) are noted on the small saddle of the mountain slope of southwestern exposure (site 3), where the snow cover melts earlier than at other sites. The latest dates for the start of thawing (June 24–July 1) were recorded at the mountain pass (site 1), where snow melting is the latest due to the formation of snow blows, since this area is located at

Table 2. **Comparison of mean annual air temperatures (°C) at the IGY weather station and the lower Agayakan and Vostochnaya weather stations**

Accounting year	Agayakan (777 m a.s.l.)	Vostochnaya (1286 m a.s.l.)	IGY (2070 m a.s.l.)
1956/57	−16.2	−13.2	−14.1
1957/58	−17.9	−14.9	−14.9
1960/61	−15.1	−13.5	−12.9
1961/62	−15.7	−12.9	−13.6
1962/63	−14.6	−13.3	−13.1
2011/12	–	−12.3	−12.1

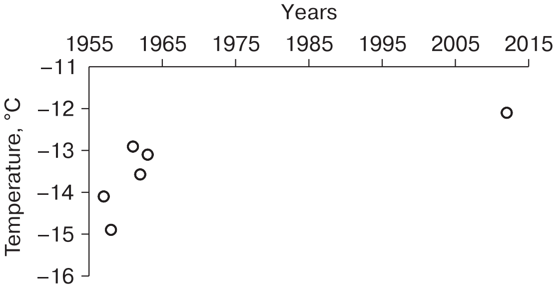

Fig. 5. Mean annual air temperature at the IGY weather station site in different years.

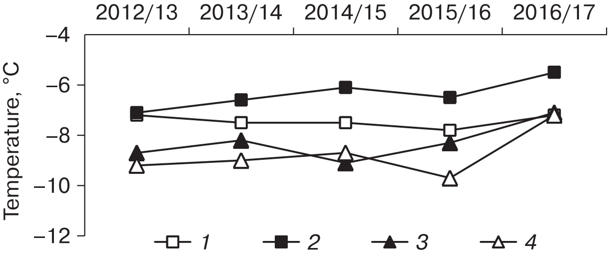

Fig. 6. Mean annual temperature of rocks at a depth of 1.2 m for the entire observation period.

1 – site 1; *2* – site 2; *3* – site 3; and *4* – site 4.

Table 3. **Thawing rates in seasonally thawed layer of soils at experimental sites in 2013–2017**

Experimental site	Relief shape	Soil composition	STL thawing start dates	Depth interval, m	Thawing rate, cm/day
1	Mountain pass	Crushed stone, debris, blocks	June 24–July 1	0.0–0.6	6.0–12.0
				0.8–1.2	0.9–1.5
2	Erosion terrace of the Burgali River	Pebbles, gravel, coarse sand	June 9–June 15	0.0–0.4	3.6–8.0
				0.4–0.8	1.5–3.6
				0.8–1.2	1.0–1.3
3	Small saddle on a mountain slope	Loamy sand, sand, debris	May 30–June 13	0.0–0.4	3.1–6.0
				0.4–0.8	1.1–1.8
4	Moraine ridge	Pebbles, gravel, boulders	June 5–June 22	0.0–0.4	4.0–13.0
				0.4–0.8	1.9–6.0
				0.8–1.2	1.0–1.6

the foot of the mountain slope. The highest rates of thawing at the beginning of summer were observed on a mountain pass (6–12 cm/day) and a moraine ridge (4–13 cm/day), where fine material in the STL is practically absent. The lowest thawing rates at the beginning of summer are characteristic of the small saddle of the mountain slope (3.1–6.0 cm/day), where fine-textured sediments predominate in the STL. At the end of the summer season, the rates of rock thawing in the lower part of the STL do not differ much at the studied sites (Table 3).

Freezing of rocks at the sites mainly began in the first ten days of September, and only in the winter of 2014/15 it was abnormally late (September 17–18). The dynamics of the freezing process over five winters was studied using temperature data at site 3 on a small saddle of a mountain slope, where near-surface deposits are represented by gravelly loamy sands and sands (Fig. 7). Due to the low mean annual permafrost temperature (–8°C), freezing of the STL here occurs actively not only downward from the surface but also upward from the permafrost table. In different years during the observation period, the freezing rate at site 3 varied from 1.3 to 2.8 cm/day for the freezing front moving downward from the surface and from 0.7 to 1.0 cm/day for the freezing front moving upward from the permafrost table. Thus, 60–70% of the STL thickness freezes from the top and 30–40%, from the bottom.

Data on glacier ice temperature for the initially selected sensor depths can be considered correct only in the first year of measurements, since due to the melting of the surface layer of the glacier during the warm period, the position of the temperature sensors relative to the glacier surface changes in subsequent years. The thickness of the melted ice layer near the boreholes was determined by the authors at the end of August by measuring the length of the wire set exposed to the surface. In the middle part of the glacier, in the summer of 2013, a layer of ice with a thickness of 1.2 m melted out; in the summer of 2014, 0.8 m; and in the summer of 2015, 2.2 m. In the upper part of the glacier, ice melting over the indicated years amounted to 1.2, 0.4 and 1.9 m, respectively. From the data presented, it is clear that both temperature measurement sites on the glacier are in the ablation zone. This is consistent with the data of glaciologists, according to which on glacier No. 31 there was practically no accumulation zone in 2012–2014, and the mass balance was consistently negative [*Mavlyudov, Ananicheva, 2016*].

According to geophysical survey in 2012–2013, the thickness of the glacier along the axial line in the middle part was estimated at 90–120 m, and in the upper part, at 120–150 m. Figure 8 shows seasonal variations in glacier ice temperature at depths of 3, 5, and 10 m for the first year of observations from September 2012 to September 2013 for the middle and

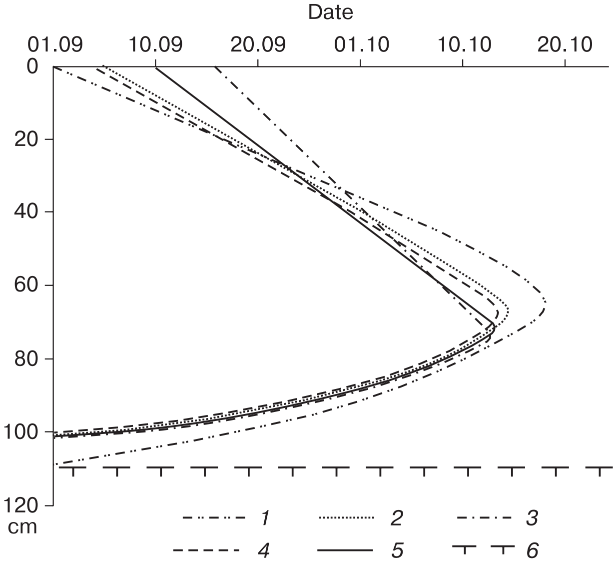

Fig. 7. Dynamics of freezing of the seasonally thawed layer at site 3 during the winter seasons from 2012 to 2017.

1 – 2012/2013, *2* – 2013/2014, *3* – 2014/2015, *4* – 2015/2016, *5* – 2016/2017; *6* – permafrost table.

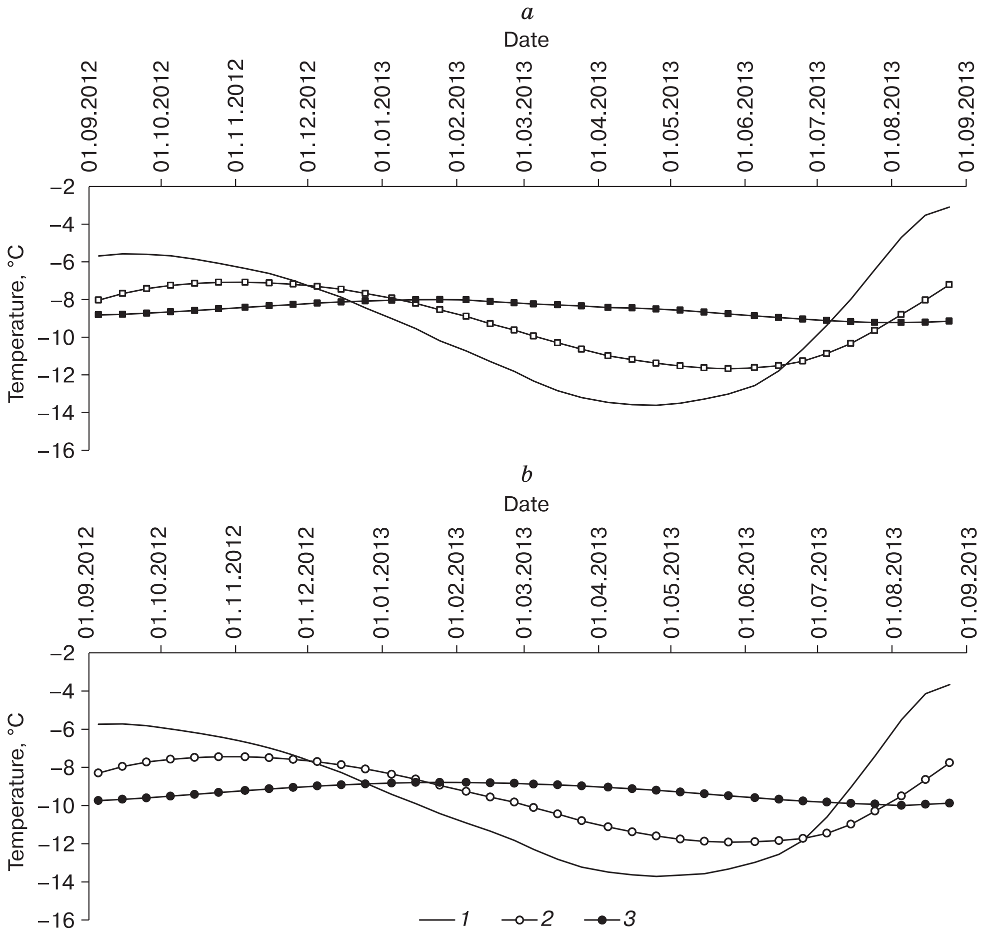

Fig. 8. Seasonal fluctuations in the temperature of glacier ice at depths of (*1*) 3, (*2*) 5, and (*3*) 10 m in the middle (*a*) and upper (*b*) parts of glacier No. 31 from September 2012 to September 2013.

upper parts of the glacier. The ice temperature in the middle part of the glacier at depths of 3 and 5 m varied from −3.1 to −11.7°C throughout the year, and in its upper part – from −3.7 to −11.9°C. At a depth of 10 m, these changes were from −8.0 to −9.2°C and from −8.8 to −10.0°C, respectively. As can be seen, the difference in the temperature of glacier ice between its middle and upper parts is greater at a depth of 10 m. At a depth of 3 m, the maximum ice temperature in both areas is observed in mid-September, and the minimum at the end of April. At a depth of 5 m, the maximum and minimum temperatures occur, respectively, at the end of October and in mid-May. At a depth of 10 m, the maximum increase in ice temperature occurs in mid-January, and the greatest decrease occurs in early August.

Of greatest interest is the comparison of the temperatures of rocks and glacier ice obtained in 1957–1959 and 2013–2017. Unfortunately, the boreholes at the weather station site drilled during the research period under the IGY program were filled with soil at the time of the Russian–Japanese expedition, so measurements in them turned out to be impossible.

Table 4 shows the mean monthly and mean annual temperatures of rocks at the weather station site at depths of 1, 1.2, and 20 m obtained during measurements in 1957–1959 and in 2012–2017. In 2012, temperature loggers were installed in close proximity to the old temperature boreholes. As can be seen from the data in Table 4, the difference in t_{ma} at a depth of 1 m in 1957/58 and 1958/59 calculation years was significant (2.2°C). This is explained by large differences in snow accumulation conditions in these years. Based on materials from the IGY expedition in the winter of 1957/58, already by the beginning of December, the thickness of the snow cover was 71 cm and reached 100 cm by the end of winter. On the contrary, in the winter of 1958/59, the thickness of the snow cover was only 31 cm by the beginning of December and did not exceed 50 cm by the end of winter. Thus, t_{ma} obtained in 1957/58 and 1958/59 calculation years cannot be considered close to the long-term average value of t_{ma} at a depth of 1 m in that period. The possible influence of air convection on the temperature of rocks in the upper parts of the boreholes that were not covered with soil should also

Table 4. **Mean monthly and annual rock temperatures at the IGY weather station site at depths of 1, 1.2, and 20 m based on measurements in 1957–1959 and 2012–2017**

Year	Depth, m	Months												Mean annual temperature, °C
		IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	
1957/58	1.0	–0.6	–3.4	–6.5	–9.9	–12.2	–14.2	–15.3	–15.2	–13.8	–9.6	–3.0	–1.3	–8.7
	20.0	–8.7	–9.0	–8.8	–8.8	–8.7	–8.6	–8.7	–8.7	–8.7	–8.8	–8.8	–8.9	–8.8
1958/59	1.0	–1.1	–4.5	–10.7	–15.7	–18.4	–20.1	–19.9	–18.2	–14.4	–4.6	–2.0	–0.8	–10.9
	20.0	–8.9	–8.8	–8.9	–8.8	–8.8	–8.8	–8.8	–8.8	–8.8	–8.9	–9.0	–9.1	–8.9
2012/13	1.2	–0.3	–2.6	–5.8	–9.2	–11.6	–12.8	–13.9	–13.6	–11.5	–3.5	–1.1	–0.1	–7.2
2013/14	1.2	–0.3	–3.7	–7.0	–9.2	–11.6	–13.4	–13.5	–13.2	–11.7	–4.2	–1.4	–0.4	–7.5
2014/15	1.2	–0.2	–3.3	–6.6	–9.4	–11.5	–12.8	–13.8	–13.7	–12.4	–4.7	–1.2	–0.2	–7.5
2015/16	1.2	–0.3	–3.0	–6.3	–9.7	–12.4	–14.5	–15.4	–14.4	–12.9	–3.2	–1.3	–0.2	–7.8
2016/17	1.2	–0.7	–3.5	–6.1	–9.0	–11.1	–12.1	–12.4	–12.2	–11.4	–5.7	–1.4	–0.3	–7.2

be taken into account. Based on the above considerations, the calculation of the temperature gradient in the depth range of 1–20 m according to data from operational measurements in 1957–1959 does not seem possible.

In 2012–2017, the range of interannual variability of t_{ma} at a depth of 1.2 m was only 0.6°C, which suggests the similarity of the main external conditions (air temperature, snow depth) that determined the thermal conditions of the near-surface layer of rocks in those years. The thickness of the STL at the weather station site was 1.1–1.2 m, so a depth of 1.2 m can be taken as the upper surface of the permafrost. From all this, it is quite reasonable to take the average value of t_{ma} at a depth of 1.2 m for five calculated annual periods as the average long-term value of the permafrost table temperature during the period of the Russian–Japanese expedition. If the temperature gradient in the layer of annual heat turnover in the research area is known, then it is not difficult to determine the permafrost temperature at a depth of 20 m in 2012–2017. According to the IGY expedition, the depth of zero annual amplitude of temperature at the weather station site was 23 m [*Grave, 1962*]. Therefore, a depth of 20 m can be approximately taken as the lower boundary of the layer of annual temperature fluctuations. Thus, a comparison of the measured temperature of rocks at a given depth in 1957–1959 with the gradient calculated for the period 2012–2017 will make it possible to quantify the increase in permafrost temperature at the base of the layer of annual heat turnover for the period 1957–2017.

The geothermal gradient within the Suntar-Khayata Ridge was measured in its western part, where the Nezhdaninskoye polymetallic ore deposit is located. For the high-mountain zone of this part of the ridge, it is 1.2–1.4°C/100 m [*Balobaev, Levchenko, 1978*]. From this we can conclude that for every meter of depth the temperature of permafrost increases by an average of 0.013°C. At a depth of 1.2 m, the t_{ma} for five calculation years from 2012/13 to 2016/17 was equal to –7.4°C. If we use the above value of the geothermal gradient, then at the weather station site at a depth of 20 m in the period between 2012 and 2017, t_{ma} can be considered equal to –7.2°C. In 1957–1959 the measured t_{ma} at a depth of 20 m was –8.8°C. As a result, it turns out that at a depth of 20 m t_{ma} changed from –8.8°C in 1957–1959 to –7.2°C in 2012–2017. Thus, at the site of the IGY weather station, the permafrost temperature at the lower boundary of the layer of annual heat turnover over the period from 1957 to 2017 increased by 1.6°C. The result obtained should be considered approximate, since, firstly, the calculation used the value of the geothermal gradient, which was not obtained directly at the research site; secondly, in the depth range of 1–20 m, the value of the geothermal gradient in the period 2012–2017 could be less than the value of this gradient for the entire permafrost layer. Taking into account the second assumption, the obtained value of 1.6°C can be considered the maximum possible increase in rock temperature at a depth of zero annual amplitude of temperatures.

During the work of the IGY expedition, the temperature of glacier ice at depths of 3–10 m was measured only for several months, so comparison with the data of the Russian–Japanese expedition is only possible based on monthly values of ice temperatures. Table 5 shows the mean monthly ice temperatures at different depths from September to December measured at the same site in the middle part of glacier No. 31 in 1958 and 2012. In 2012, at depths of 3, 5, and 10 m, the mean monthly ice temperature was higher than that in 1958 by 0.9–2.5, 1.5–2.4 and 1.0–1.6°C, respectively. Since the measurements were carried out over a very short period, to compare the temperature conditions of glacier ice for the indicated years, it is better to limit ourselves to a depth of 10 m, where the influence of interannual variability of external conditions on the surface is minimal. At this depth, the temperature of glacier ice in 2012 for four months from September to December was 1.0–1.6°C higher than in 1958.

Table 5. **Mean monthly temperatures of glacier ice in the middle part of glacier No. 31 in 1958 and 2012**

Depth, m	September		October		November		December	
	1958	2012	1958	2012	1958	2012	1958	2012
3	−7.0	−5.6	−7.0	−5.9	−7.6	−6.7	−10.4	−7.9
5	−10.1	−7.7	−8.7	−7.2	−8.7	−7.1	−9.0	−7.5
10	−9.8	−8.8	−9.8	−8.6	−9.8	−8.3	−9.7	−8.1
20	−9.2							
45	−7.8							

CONCLUSION

Temperature measurements carried out by the Russian–Japanese expedition in 2012–2017 in the same areas, where the IGY expedition worked in 1957–1959, made it possible to quantify the impact of climate warming on the thermal conditions of permafrost and glacier ice in the high-mountain part of the Suntar-Khayata Ridge. A comparison of mean monthly temperatures of glacier ice at a depth of 10 m for 1958 and 2012 showed an increase by 1.0–1.6°C. Over the past 60 years, in the research area, the temperature of rocks at a depth of zero annual amplitude of temperatures, according to a rough estimate, could have increased by a maximum of 1.6°C. Due to the low-temperature permafrost, the freezing of the seasonally thawed layer here proceeds actively not only downward from the surface but also upward from the permafrost table. Thus, 60–70% of the thickness of the seasonally thawed layer freezes from the top, and 30–40%, from the bottom.

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