

GEOCRYOLOGICAL MONITORING AND FORECAST

DYNAMICS OF PERMAFROST TEMPERATURE REGIME IN DEEP BOREHOLES
IN THE CENTRAL PART OF NORILSK

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In the Arctic zone, the current rise in air temperatures is much faster than in the central part of Russia. This leads to an increase in the temperature of frozen ground of the foundations of buildings and engineering structures, a decrease in their bearing capacity, and an increasing risk of their destruction. At the same time, the temperature regime of frozen ground in the city depends on many factors (microclimatic features, composition and properties of soils, technogenic influence, maintenance practices). In 2022, as part of the program to create an element of a unified system for monitoring the state of permafrost in the municipality of the city of Norilsk and the Taimyr Dolgano-Nenets municipal district, the Polar Division of PJSC MMC Norilsk Nickel began a program for constructing deep boreholes in the territory of the company's responsibility both in the natural environment (as part of the background permafrost monitoring) and in the city. The purpose of this article is to assess the dynamics of the temperature regime of permafrost in the center of Norilsk. Archival materials (since 1959) and the results of geotechnical surveys conducted in Norilsk to study the geological structure, composition, and properties of frozen rocks have been analyzed, and monitoring measurements in a new thermometric borehole drilled to replace the previous one, have begun. The data obtained indicate a significant change in the geocryological conditions in the city. Over the past 65 years (from 1959 to 2024), the ground temperature at a depth of 10 m in the area of the deep thermometric borehole increased by 4.3°C. Significant temperature fluctuations have been recorded down to a depth of 90 meters, and further down the section to a depth of 200 meters the temperature has changed by an average of 0.3°C.

Keywords: frozen ground, permafrost, temperature regime, climate change, Arctic city, Norilsk.

Recommended citation: Kotov P.I., Pryamitskiy A.V., Kunchuliya G.M., 2025. Dynamics of permafrost temperature regime in deep boreholes in the central part of Norilsk. *Earth's Cryosphere* XXIX (1), 3–11.

INTRODUCTION

Currently, there are 1162 settlements with about five million inhabitants in the Arctic permafrost zone. Most settlements are small, with an average population of 622 residents. Eighty-five percent of large settlements are located in the Russian Arctic [Ramage et al., 2021]. Norilsk agglomeration is one of the largest in the Arctic, home to over 183 000 people. The main problems of the city's life support are due to harsh climatic conditions, remote location, and the specific operating conditions of buildings and engineering structures [Shiklomanov et al., 2017].

Geocryological conditions in the Norilsk industrial region are extremely heterogeneous. The thickness of permafrost varies from 5 to 800 m or more, and significant areas (up to 40%) in the intermontane valleys are occupied by taliks, even in the north of the region. Mean annual temperature of the rocks varies in a wide range: from –7 to +2°C [Ershov et al., 1989]. Climate change in the Arctic territories is becoming one of the most important global problems. The warming trend in the Arctic exceeds the global average by more than 2.5 times. Almost all forecasts show that the area of permafrost will decrease [Rosgidro-

met, 2022]. Globally, permafrost temperature has increased by $(0.29 \pm 0.12)^\circ\text{C}$ since 2007 [Biskaborn et al., 2019].

Global warming leads to the thawing of permafrost, a key component of Arctic territories, which poses a significant threat to the integrity of polar infrastructure. Studies have been conducted on climate change and its impact on engineering structures [Grebenets, Sadovsky, 1993; Grebenets, Ukhova, 2008; Hjort et al., 2018, 2022; Streletskiy et al., 2019; Porfiryev et al., 2019; Melnikov et al., 2022; Falaleeva et al., 2023]. However, these estimates are general and are not based on factual material on the geological structure, geocryological conditions, and construction principles, though these characteristics may vary even within the same urban area. In this regard, the most reliable results are those of mathematical modeling performed on the basis of actual measurement data for a specific object [Schneider von Deimling et al., 2021; Hjort et al., 2022]. For example, a significant part of the industrial buildings and engineering structures of the Polar Division of PJSC MMC Norilsk Nickel are located on rocky or thawed soils, so cli-

mate change will not affect their stability. However, historically, the urban area of Norilsk was built using technical solutions for construction on permafrost soils [Grebenets, Sadovsky, 1993; Makarov et al., 2001; Setkov et al., 2005; Shiklomanov et al., 2017].

The construction of multi-story residential and public buildings in the southern part of the city was carried out mainly in the 1940s–1950s. All these buildings were constructed on hard bedrock as the natural foundation. One of the main features of the construction was sufficient deepening of the foundations into the bedrock, because its upper part was strongly destroyed by weathering processes. In such rocky massifs, cracks are sometimes filled with ice inclusions, which, when changing from a frozen to a thawed state, can cause displacement of structures and subsidence of thawing soils in the adjacent territory. The depth of deepening into the bedrock, depending on the thickness of the destroyed zone, ranged from 0.1 to 2.0 m and more [Makarov et al., 2001]. Operating experience shows that if the deepening was done well and below the cracked zone, the building is currently in operation without significant problems. In conditions of deeper bedrock (more than 10 m), concrete columnar foundations with support on coarse-grained soils with low ice content were used in Norilsk. Most of the buildings located in the area of the Nickel Plant (the first metallurgical plant) were built on such soils [Setkov et al., 2005].



Fig. 1. Location of the study area (marked in red).
1 – borehole TN-1.

In the late 1950s, pile foundations proposed by M.V. Kim [Kim, 1964, 1967] began to be used for further construction in the city. The new construction sites were mainly found in the areas of frozen dispersed soils and were characterized by complex geocryological conditions with mean annual permafrost temperatures of -2 to -4°C and the presence of talik zones and ice-rich soils.

Because of these challenging conditions, a 200-m-deep borehole was drilled in the then-undeveloped area in 1959, where temperature measurements were subsequently taken. Recently, these measurements have been resumed after a long pause, which allows us to estimate the temperature dynamics of permafrost soils in the center of Norilsk from 1959 to 2024.

STUDY AREA AND WORK PROCEDURE

The territory of the municipal formation of the city of Norilsk is located north of the Arctic Circle, in the zone of permafrost soils and belongs to the continental part of the Arctic.

This region is characterized by a harsh subarctic climate with the mean annual air temperature (Norilsk station) of -9°C (1934–2023). Winters are long and severe, with the absolute minimum air temperature of -57°C . Summer with above-zero mean daily air temperatures lasts for only four months, and the mean monthly temperature of the warmest month is 18.5°C .

The study area is a built-up area in the central part of Norilsk (address: Leninsky Prospekt, 25A), in the immediate vicinity of the site, there are operating buildings and structures for various purposes (Fig. 1).

In this part of the city, there was a 200-m-deep borehole (D-1284 in Fig. 2) was drilled, and temperature measurements in it began as early as in 1959. However, it was destroyed in the early 2000s. In 2022, as part of the program for monitoring the state of permafrost in Norilsk and Taimyr Dolgano-Nenets

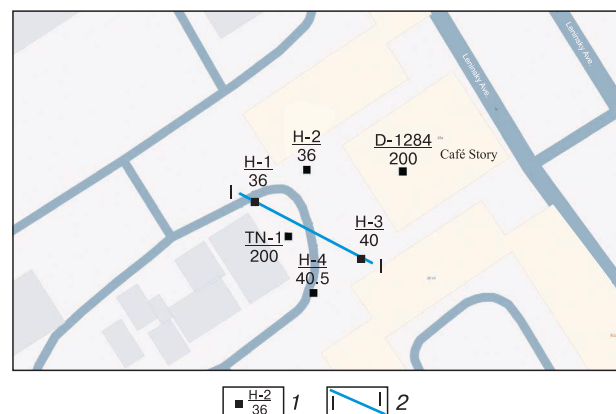


Fig. 2. Location of boreholes in the study area.

1 – borehole number and depth, 2 – line of the engineering-geological section.

municipal district, the Polar Division of PJSC MMC Norilsk Nickel decided to continue monitoring studies of the temperature regime in the city. In this regard, a new 200-m-deep borehole was drilled 30 m from its original location (borehole TN-1 in Fig. 2), and engineering and geological work was carried out to determine the variability of the geological structure and soil properties in the territory (boreholes H-1 to H-4 in Fig. 2). Engineering and geological surveys were carried out by the Norilsk Nickel Technical Services LLC and included the following works:

- Borehole drilling. It was performed using a mechanical core “dry” drilling method with a shortened run and minimum rotation speed of the drill, with full core sampling and careful description of core samples and soils of the mine workings;

- Laboratory determination of the physical thermophysical properties of soils in accordance with current regulatory documents;

- Soil temperature measurements in the borehole conducted in accordance with [GOST (State Standard) 25358-2020, 2020]. The set for field measurement of soil temperature consists of a thermocouple and an ETC-0.1/10 digital electrometer. Temperature measurements using thermometric strings were performed with a spacing of 0.5 m to a depth of 5 m, 1 m (at depths of 5–10 m), and 2 m (down to the borehole bottom). The zero sensor was placed on the ground surface. Before the measurements, the borehole was left to stand for 14 days.

The drilling of the 200-m-deep borehole began in October 2022. The drilling diameter in the loose Quaternary sediments was 122.6 mm; deeper, in the bedrock interval, 96 mm. Geological documentation and photo documentation of the core were carried out during the drilling.

Upon completion of drilling, a casing pipe of 89 mm in diameter was installed and the annulus was cemented; the cement was allowed to harden for 48 h. Then, the borehole was pressured up with compressed air.

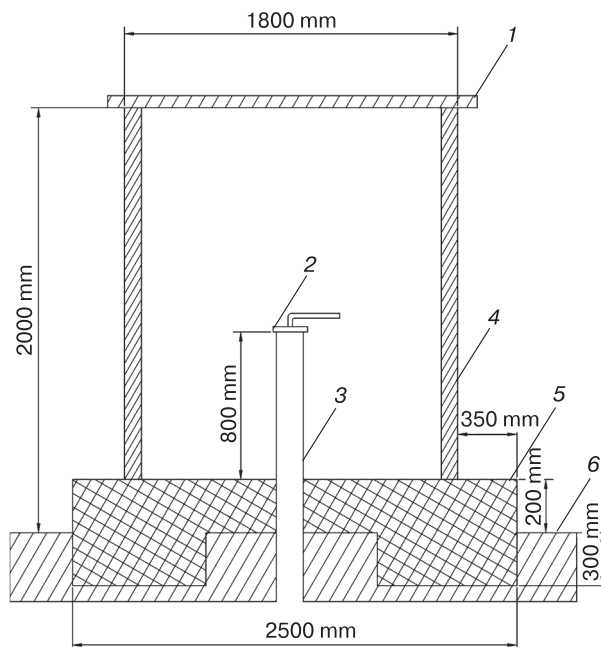


Fig. 3. Diagram of the borehole capping structure.

1 – manhole cover, 2 – device for automatic data transmission, 3 – head, 4 – walls, 5 – concrete slab, 6 – soil.

After drilling and preparing the borehole, a capping structure was installed (Fig. 3) to protect against the negative impact of environmental factors and eliminate the possibility of demolition.

In March 2023, the first soil temperature measurements were taken in the new 200-m-deep borehole; continuous monitoring measurements began in December 2023.

RESULTS

The geological structure of borehole TN-1 is represented by the Lower Triassic intrusive rocks ($\nu\beta T_1$) and Quaternary Ayaklin lacustrine sediments

Table 1. Characteristics of engineering-geological units

EGU no.	Index	Description
1.1	tIV	Filled soil: gravelly soil, frozen, with filler (30.4%) in the form of slightly saline loam, solid in the thawed state, with a medium degree of water saturation
1.2t	tIV	Filled soil: gravelly sand, medium water saturation, medium density, with an admixture of organic matter
1.3t	tIV	Filled soil: fine sand, medium water saturation, medium density
2	IIII–Hak	Silty sand, frozen, icy; in a thawed state – water-saturated, loose
3	IIII–Hak	Sandy loam, frozen, icy; fluid when thawed
4	IIII–Hak	Sandy loam, frozen, low ice content; fluid-plastic when thawed
5	IIII–Hak	Coarse sand, frozen, low ice content; moderately water-saturated in a thawed state, loose
6	IIII–Hak	Loamy sand, frozen, low ice content; plastic in a thawed state
7	IIII–Hak	Medium-grained sand, frozen, low ice content; moderately water-saturated in a thawed state, loose
8	IIII–Hak	Sandy loam with gravel and pebbles, frozen, no visible ice; semi-solid when thawed
9	IIII–Hak	Medium-grained sand, frozen, low ice content; moderately water-saturated in a thawed state; medium density
10	IIII–Hak	Silty sand, frozen, low ice content; water-saturated in a thawed state, medium density
11	$\nu\beta T_1$	Bedrock (gabbro-diabase), very strong, very dense, non-porous, non-softening

(III–Hak). Human-made soils—coarse-grained and sandy—clayey layers – are found at the top of the section. Human-made soils were formed during construction and surface planing by adding imported soil to the design level. At the time of the survey (September 2022), groundwater was not discovered at the work site.

Analysis of field and laboratory data from engineering and geological surveys made it possible to identify 13 engineering-geological units (EGUs) in this territory to a depth of 200 m (Table 1).

The geological section obtained on the basis of engineering and geological surveys is shown in Fig. 4. The difference in the structure of the section in the

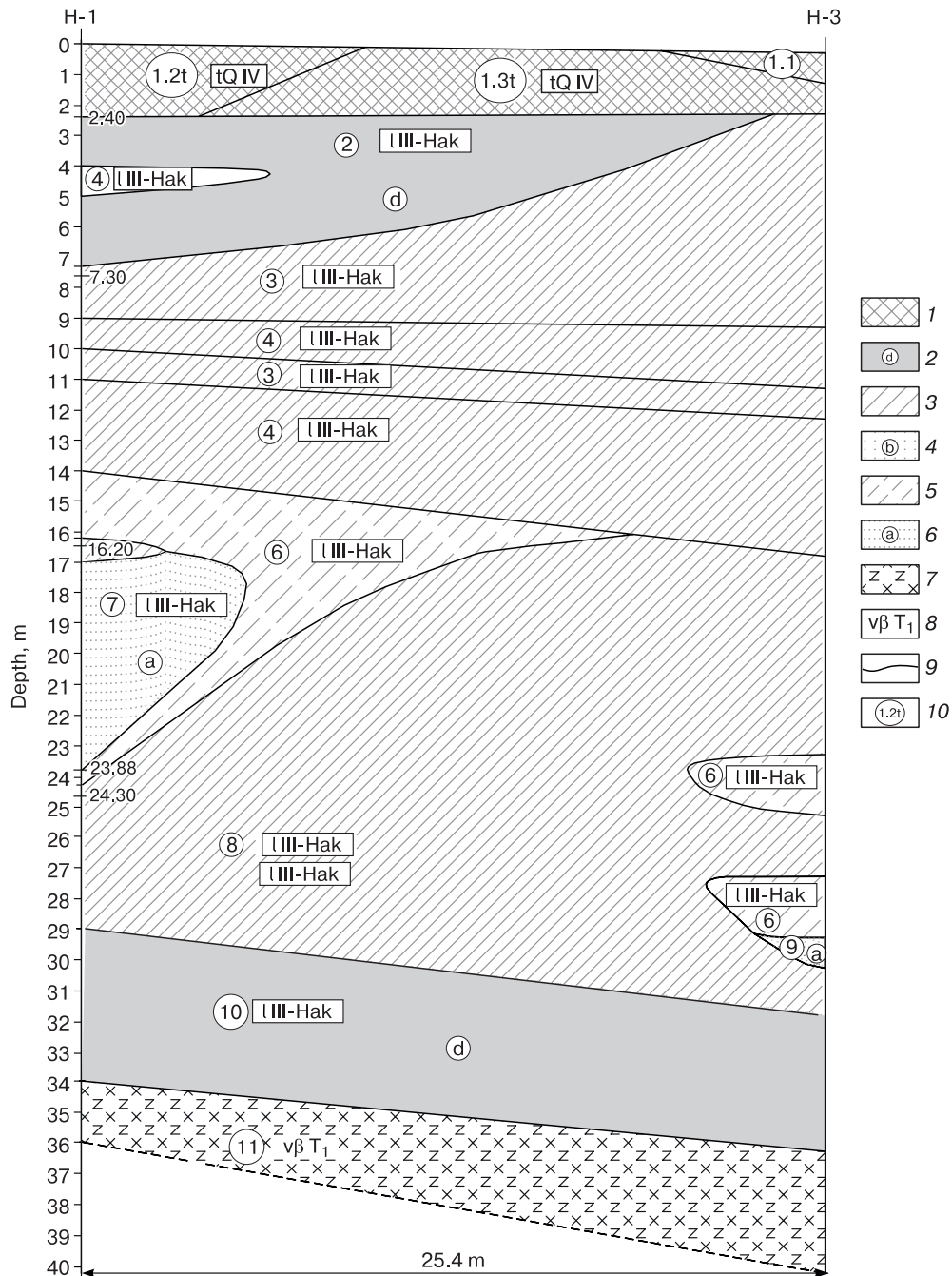


Fig. 4. Geological section along line I–I.

1 – filled soil, 2 – silty sand, 3 – loam, 4 – coarse sand, 5 – loamy sand, 6 – medium-grained sand, 7 – hard rock, 8 – geological index, 9 – EGU boundary, 10 – EGU number designation (description of EGUs is given in Table 1).

Table 2. Calculated characteristics of the soil properties at the site

EGU no.	ρ	ρ_s	w	w_L	w_p	i_{tot}	i_i	D_{sal}	T_{bf}	λ_{th}	λ_f
	g/cm ³		fraction unit					%	°C	$\frac{W}{(m \cdot ^\circ C)}$	
1.1	2.33	2.81	0.06	0.21	0.13	0	0	0.22	–	–	–
1.2t	1.98	2.78	0.14	–	–	–	–	–	–	1.12	–
1.3t	2.02	2.82	0.17	–	–	–	–	–	–	2.07	–
2	1.83	2.81	0.30	–	–	0.46	0	0.08	–0.19	1.65	1.95
3	1.77	2.82	0.36	0.26	0.16	0.4	0.23	0.09	–0.19	1.21	1.6
4	1.87	2.84	0.26	0.27	0.17	0.31	0.1	0.1	–0.2	1.37	1.59
5	1.94	2.83	0.20	–	–	0.36	0	0.08	–	1.81	2.22
6	1.96	2.84	0.19	0.18	0.12	0.26	0.06	0.11	–0.2	1.29	1.54
7	1.89	2.82	0.22	–	–	0.37	0.01	0.07	–0.17	1.71	2.1
8	2.03	2.83	0.14	0.23	0.14	0.15	0	0.09	–0.2	1.25	1.63
9	1.95	2.83	0.17	–	–	0.31	0	0.06	–	1.9	2.46
10	1.94	2.81	0.23	0.00	0.00	0.39	0	0.07	–0.21	2.25	2.25
11	2.9	2.97	0.01	–	–	–	–	–	–	–	–

Note: ρ is the soil density; ρ_s is the soil solid phase density; w is the total soil moisture content for frozen soil, natural soil moisture content for thawed soil; w_L is the upper plasticity limit moisture content; w_p is the lower plasticity limit moisture content; i_{tot} is the total ice content; i_i is the ice content due to visible ice inclusions; D_{sal} is the content of soluble salts; T_{bf} is the soil freezing onset temperature; λ_{th} is the thawed soil thermal conductivity coefficient; and λ_f is the frozen soil thermal conductivity coefficient.

areas of boreholes H-1 and H-3 (spaced apart at 25 m) is clearly seen. In the area of borehole H1, layers EGU 4, EGU 6, and EGU 7 appear, and gabbro-diabase layer (EGU 11) extends down to 200 meters.

Statistical processing of data on soil properties was carried out in accordance with [GOST (State Standard) 20522-2012, 2020]; normative and calculated characteristics of physical and thermophysical properties of soils were determined by laboratory methods (Table 2).

In the upper part of the section (EGU 1.1–EGU IGE 1.3t) to a depth of 1–3 m, there are human-made (technogenic) soils, mainly within the seasonally thawed layer. The thickness of technogenic soils is self-compacted; since the time of construction, it has been caked. Due to the chaotic nature of the fill and the uneven composition of technogenic soils, anisotropy in the physical and thermal properties of these soils is noted.

Differences in the geological structure, insolation patterns, and heat emission from nearby buildings af-

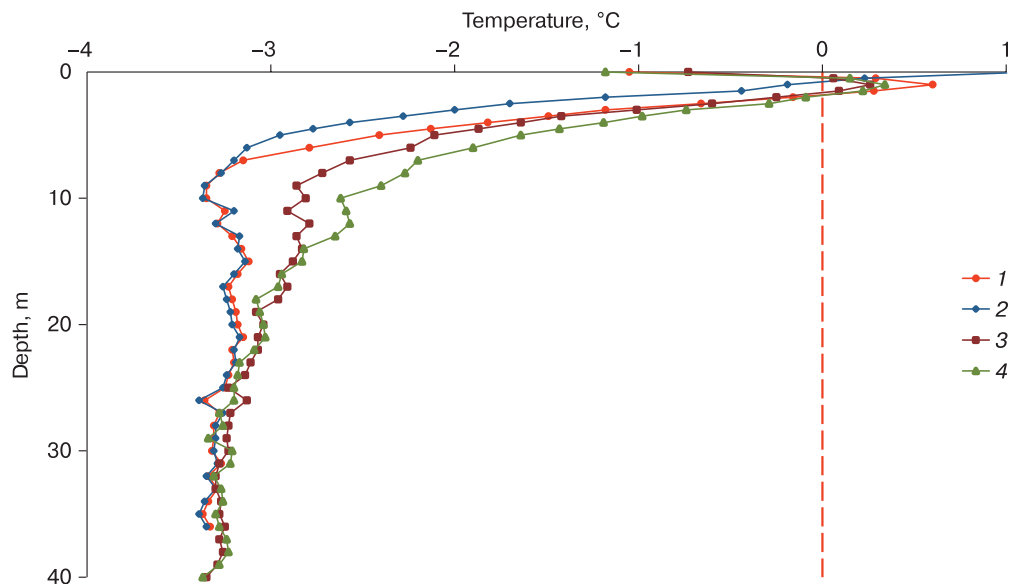


Fig. 5. Soil temperature in the deep well area in September 2022.

1 – borehole H-1; 2 – borehole H-2; 3 – borehole H-3; 4 – borehole H-4.

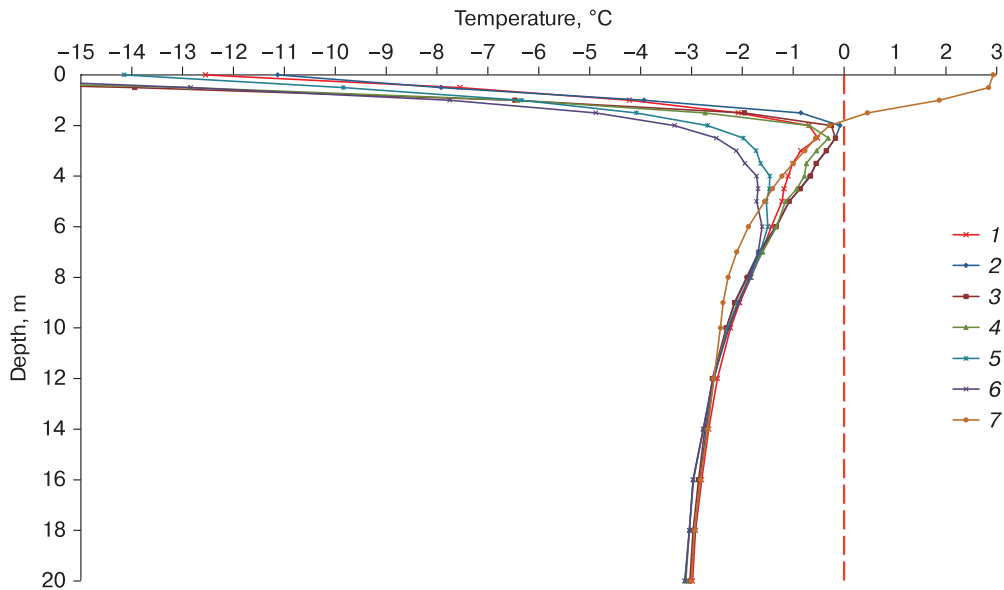


Fig. 6. Soil temperature regime in well TN-1.

1 – Mar. 27, 2023; 2 – Dec. 22, 2023; 3 – Jan. 14, 2024; 4 – Feb. 15, 2024; 5 – Mar. 15, 2024; 6 – Mar. 27, 2024; 7 – Sept. 15, 2024.

fect the temperature regime in the boreholes. At the same time, a significant difference in temperatures is observed for boreholes H-1 and H-2 on one side of the site, and H-3 and H-4 on the opposite side (Fig. 5). At a depth of 10 m, the difference reaches 1°C ; at a depth of 30 m, it virtually disappears, which attests to significant technogenic influence in the upper part of the section. The presence of underground heat-generating collector systems for sanitary and technical utilities in this area may be one of the reasons for such a significant difference in temperature between boreholes H-1, H-2 and H-3, H-4. However, no surveys of the utilities have been conducted.

In March 2023, the first temperature measurements were taken in a new 200-m-deep borehole, and continuous monitoring measurements began in De-

cember. For 1.5 years, temperature fluctuations have been observed to a depth of 12 m; below, the temperature remains virtually unchanged (Fig. 6). Observations will be continued to confirm the stabilization of the temperature regime around the new borehole.

DISCUSSION

The data obtained at the Norilsk weather station indicate that the mean annual air temperature has increased since the mid-1980s (Fig. 7). In the Norilsk industrial region, the rate of this increase reaches $0.7^{\circ}\text{C}/\text{decade}$. In the recent years, abnormally warm annual air temperatures have been recorded, such as -3.78°C (in 2020), against the mean annual air temperature of -8.98°C for the period from 1934 to 2023. The rate of warming varies by season, with the greatest temperature rise in the spring season.

In general, the climate in the study area has become more humid in the past few decades due to an increase in precipitation and changes in its fallout patterns.

Changes in precipitation and air temperature have led to changes in the snow accumulation regime. The formation of the snow cover begins 5–10 days later, and the breakdown of the snow cover takes place about 5 days later.

When analyzing the temperature regime based on stationary observations in urban environments, it is necessary to take into account the urban heat island effect – the difference between air temperatures in the city and in the surrounding area – associated

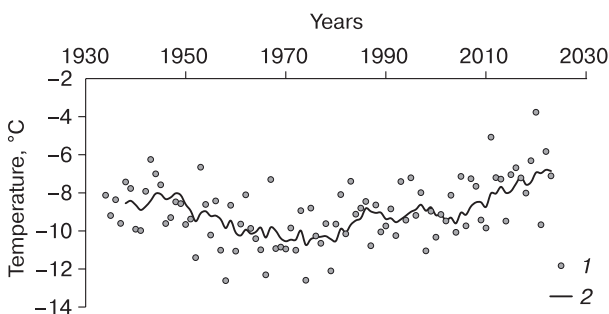


Fig. 7. Change in the mean annual air temperature according to Norilsk weather station data from 1934 to 2023.

1 – actual temperature values; 2 – seven-year averages.

with the local influence of urban development and heat sources in the city. One of the main reasons for the appearance of urban heat island is related to a more efficient absorption and retention of solar heat by the city [Ryu, Baik, 2012]. For polar night conditions in winter in northern cities of Russia, the results of numerical modeling of the urban heat island showed a significant contribution of the anthropogenic factor (due to direct heating) to the formation of this phenomenon [Varentsov *et al.*, 2018].

The paper [Esau *et al.*, 2021] presents an analysis of the characteristics of the urban heat island for settlements in the Arctic with a population of more than three thousand people. For Norilsk, the average intensity of the urban heat island in the recent decades has averaged $+2.7^{\circ}\text{C}$ in summer and $+3.2^{\circ}\text{C}$ in winter. The intensity of the urban heat island in this case is calculated as the difference between the maximum temperature in the city and the average temperature in the region outside the city [Miles, Esau, 2017; Esau *et al.*, 2021]. However, daily values of the heat island intensity can differ greatly from the average values and reach $7\text{--}8^{\circ}\text{C}$ [Varentsov *et al.*, 2014].

To perform calculations, an important task is to assess the impact of the urban heat island on the temperature regime of soils in the city. To assess this factor, a comparison was made between the temperature data from the zero sensor (located at the surface) in borehole TN-1 in the center of Norilsk (measurements are taken three times a day) and the air temperature at the Norilsk weather station (located 2.5 km west of the borehole, measurements are taken every 3 hours) from December 22, 2023 to May 31, 2024 (Fig. 8). As a result, it was found that there is some phase shift in temperature change in the bore-

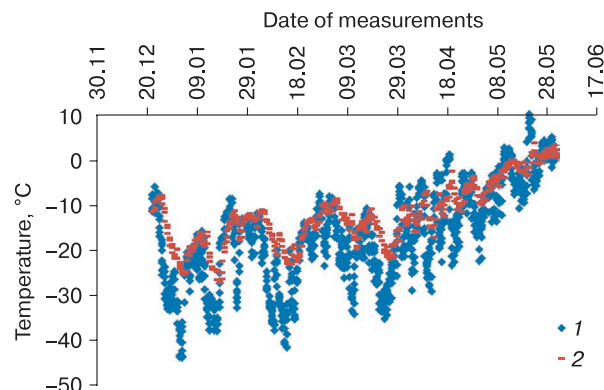


Fig. 8. Air temperature T at the Norilsk weather station and the temperature of the earth's surface in a borehole in the city center.

1 – weather station; 2 – borehole.

hole, and that its amplitude is much smaller, but the values are within the range of air temperature data variability and do not exceed them. The research will be continued, including the use of automatic meteorological stations, to identify differences in the annual cycle in the research area.

Over the past 65 years (from 1959 to 2024), the soil temperature at a depth of 10 m has increased by 4.3°C in the area of deep boreholes. Significant temperature fluctuations have been recorded to a depth of 90 m; deeper, to a depth of 200 m, the temperature has changed by an average of 0.3°C . At the same time, over the period from 1959 to 1985, the soil temperature at a depth of 10 m increased by only 1.9°C (Fig. 9).

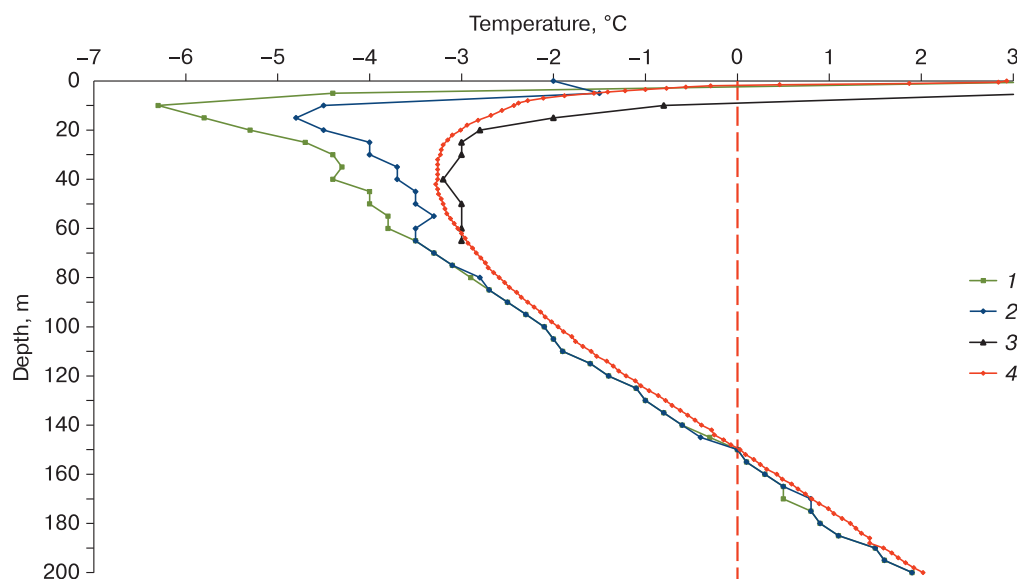


Fig. 9. Dynamics of the temperature regime of soils in the central part of Norilsk.

1 – July 1959; 2 – December 1985; 3 – July 2006; 4 – September 2024.

At the same time, the geothermal gradient has remained virtually unchanged: 3.7°C per 100 m. It is important to take into account that measurements in the 1960s–1980s were carried out using inertial thermometers, while, at present, semiconductor sensors are used, the accuracy of which is much higher. This may be one of the reasons for the discrepancies in the temperature curves below 90 m, where the influence of the technogenic factor is minimal. In addition, only next year will it be possible to assess whether the new borehole has come to the temperature equilibrium with the surrounding soil after additional heating during drilling, and whether this affects the temperature regime. Measurement data show that, in the upper part of the section, there was a sharp increase in temperature until 2006 (the temperature at a depth of 10 m was –0.8°C), which could be due to the construction of a store nearby, as well as emergency situations in the communications of houses. In the early 1990s, several accidents related to the heat and water supply of the city were recorded, which led to the need to drain water under the buildings. Man-made flooding and salinization of soils (and according to the results of laboratory studies, the salinity of soils in the seasonal thawing layer is three times higher than in the soils located below) led to a widespread increase in the depths of seasonal thawing and changes the soil temperature and hydrogeological conditions. In the period from 1997 to 2002, the largest number of house closures occurred in Norilsk due to irreversible deformation caused by the thawing of frozen soils [Kotov, Avilov, 2023].

It should also be taken into account that in 2023–2024, measurements were carried out in another borehole because it was impossible to restore the initial borehole in the same place. Snow removal was carried out at the location of the borehole (TN-1), which led to a decrease in the soil temperature in the area. Also, the new borehole is now located in a capping structure, so there is no snow cover there, and snow in the Norilsk industrial region has the greatest impact on soil temperature regime [Gribenets, Tolmanov, 2021].

Thus, for Norilsk, as for other cities in the Arctic zone, the main reasons for the increase in soil temperature are improper operation of buildings and structures, failure to take into account geocryological conditions, composition and properties of soils [Kotov, Khilimoniyuk, 2021; Brushkov et al., 2023].

As of September 2024, permafrost thickness at the site has decreased slightly – by 2.3 m over 65 years under the influence of heat flow from the subsoil: in 1959, it was 150 m, and now it is 147.7 m. However, these data are preliminary and may change due to further temperature equilibration in the deep borehole after some warming during drilling.

CONCLUSIONS

As a result of the work, temperature indicators and changes in permafrost thickness, soil composition and properties in the area of deep boreholes in the central part of Norilsk were determined, namely:

- The geological structure of the study area is represented by the Lower Triassic intrusive igneous rocks (vβT₁) and Quaternary Ayaklin lake sediments (III–Hak). Man-made soils represented by coarse-grained and sandy-clayey varieties, lie on top. In this area, 13 engineering-geological units have been identified, and the gabbro-diabase unit has the greatest thickness (more than 150 m). The geological structure on a site measuring 25 by 25 m differs significantly.

- Indicators of physical and thermophysical properties of frozen soils have been calculated for each engineering-geological unit.

- Differences in the geological structure, insolation regime of the territory, and heat emission of nearby buildings affect the temperature regime of the soils. At the same time, there is a significant difference in the temperatures obtained in September 2022 for boreholes H-1 and H-2 located on one side of the site, and H-3 and H-4, on the other side. At a depth of 10 m, the difference reaches 1°C; at a depth of 30 m, it virtually disappears, which indicates a significant technogenic impact in the upper part of this area.

- Over the past 65 years (from 1959 to 2024), there was an increase in soil temperature at a depth of 10 m by 4.3°C in the area of deep boreholes. Significant temperature fluctuations were recorded to a depth of 90 m; below, down to a depth of 200 m, the temperature changed by an average of 0.3°C.

- The geothermal gradient is 3.7°C/100 m.

The obtained data can be used to assess the impact of natural and man-made factors on the temperature regime of soils, to create well-founded forecast models verified on the basis of actual measurements, and to make scientifically sound management decisions on the functioning of urban infrastructure in Norilsk.

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Received July 15, 2024

Revised October 16, 2024

Accepted December 3, 2024

Translated by A.V. Muravyev