RESEARCH PAPER

THERMAL REGIME OF PERMAFROST ON THE WESTERN YAMAL UNDER CLIMATE WARMING

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ABSTRACT. Climate change observed in the Arctic affects all components of the natural environment, including the state of permafrost. The purpose of this study is to quantify the response of permafrost in various landscapes to changing climatic parameters. The results of long-term field observations (1978-2021) of the thermal regime of permafrost on the Western Yamal are presented. Along with the increase in mean annual air temperatures, the mean annual ground temperature over the past 43 years has increased by 1.5-2.2°C. The maximum increase of permafrost temperature values is observed on flat and polygonal tundra, the minimum increase is typical for flooded lake basins. A decrease in the annual permafrost temperature amplitude was revealed. That is caused by a rapid increase in the air temperature of the cold period, an increase in the snow thickness and an increase in soil moisture in the active layer. The shrinking in ground temperature amplitude at a depth of 5 m is 0.5-3.6°C. A trend of reducing depth of zero annual amplitude from 12-18 m (1980) to 13-16 m (2021) has been revealed.

KEYWORDS: permafrost, permafrost thermal regime, climate warming, depth of zero annual amplitude, monitoring, Western Yamal

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INTRODUCTION

Assessment of the permafrost state under conditions of climate change is a priority problem in recent decades in permafrost science (Romanovsky et al., 2010; AMAP, 2011, 2021; Stocker et al., 2013; Biskaborn et al., 2019; Noetzli et al., 2021; Streletskiy et al., 2021). The cryosphere and, in particular, permafrost, influence the planetary water and carbon cycles, the evolution of the Arctic and subarctic ecosystems, the stability of the Arctic infrastructure, etc.

It has been established that the response of the permafrost to climate change differs in time and space in the regions of the permafrost zone (Brown et al., 2000; Romanovsky, 2006; Khrustalev et al., 2008; Vasiliev et al., 2011; Streletskiy et al., 2015; Sergeev et al., 2016; Vasilchuk et al., 2017; Kaverin et al., 2017; Farquharson et al., 2019; Kotov, Khilimonyuk, 2021; Tregubov et al., 2021). Over the past 50 years, the temperature of permafrost has increased, as well as the active layer thickness (ALT); there has been a decrease in the area and thickness of permafrost near its southern boundary (Pavlov et al., 2007; Moskalenko, 2009; Drozdov et al., 2010; Dubrovin, Kritsuk, 2011; Konstantinov et al., 2014; Vasilchuk et al., 2015a,b; Biskaborn et al., 2019; Vasiliev et al., 2020). Thus, in the western part of the Russian Arctic the long-term monitoring of the thermal state of permafrost indicated permafrost temperature increase rates from 0.01 to 0.06–0.07°C/year across cryogenic landscapes (Malkova et al., 2022). At Marre-Sale area at Westen Yamal the previous studies indicated the highest rate of permafrost temperature increase in the western Russian Arctic since the 1970s with temperatures at the depth of zero annual amplitude increasing 0.06°C/year (Vasiliev et al., 2020).

No general patterns of frozen ground changes across the entire permafrost zone have been identified. In this regard, studies based on long-term observational data obtained by a single method in different regions and types of permafrost are of great importance.

The aim of the work is to reveal the changes in thermal regime of permafrost in a changing climate on the key site of Western Yamal. The results made it possible to assess the change in the thermal state of the permafrost over the past 50 years and to identify general patterns and quantitative indicators of the temperature regime for Western Yamal, which can be used for a general understanding of the processes of transformation of the permafrost.

MATERIALS AND METHODS

Study area

The study area is located on the coast of the Kara Sea near the Marre-Sale weather station (Fig. 1). The Marre-Sale research station is located in bioclimatic subzone D of a typical tundra (Walker et al., 2005; Oblogov et al., 2020) within the third marine terrace with altitudes of 15-30 m above sea level. The marine terrace is dissected by a system of water tracks, gullies and lake basins. The northern part of the research area is limited by the floodplain of the local river with absolute elevations of 0.5-3.0 m. The landscape structure of the study area is representative of the entire range of typical Yamal tundra. Lakes occupy about 12% of the territory. A comparison of data on vegetation cover dynamics over several years shows a relatively stable state of vegetation. Most species are characterized by irregularly cyclic changes in their occurrence associated with climate (Anthropogenic changes…, 2006). Although recent studies reveal NDVI changes in the Arctic since the 1980s (Walker et al., 2012; Berner et al., 2020; Jespersen et al., 2023), these changes are spatially heterogeneous and can include not only an increase but also a decrease of NDVI. In the study area, the type of vegetation cover has not changed significantly during ground temperature monitoring.

The geological profile is represented by two complexes of Late Quaternary deposits (Streletskaya et al., 2021). The upper complex is composed of continental (alluvial, lacustrine) sands and sandy loams on average 10 m thick, the lower complex is marine and shallow marine saline clays and loams with rare sand interlayers, and its visible thickness is about 20 m.

The territory belongs to the area of continuous permafrost distribution. Permafrost of the third marine terrace has a two-layer structure. The upper layer down to the depth of 90 m (Kanevskiy et al., 2005) is represented by hard frozen ground, the lower permafrost layer contains no ice due to the high salinity of the sediments. The hard-frozen rocks contain ice inclusions, lenses and interlayers of visible ice. The average annual ground temperature at a depth of zero annual amplitudes varies from -2.5 to -7.5°C depending on the location. The depth of seasonal thawing varies from 0.4 to 2.2 m depending on the type of landscape.

The thickness of the hard frozen strata on the floodplain is about 40 m. Geophysical studies have shown the presence of a closed talik up to 10 m deep under the Marre-Yakha River. The outlines of the talik repeat the relief of the channel (Melnikov et al., 2010).

Within the plains in the permafrost zone, there is a strong correspondence between the average annual temperature of frozen ground, the ALT, and the type of landscape (Landscapes of the permafrost zone ..., 1983). Each landscape is characterized by specific morphology, ground composition, moisture regime of the active layer, type of tundra soils, vegetation, temperature regime of permafrost and depth of seasonal thawing. Therefore, permafrost in dominant landscapes was chosen as the object of geocryological monitoring. To characterize landscapes, a simplified classification (von Fisher et al., 2010) was used. Landscapes and observation sites (boreholes) IDs are given in Table 1.

Western Yamal is located in the subarctic zone, a moderately cold humid Atlantic province of the Western Arctic climatic region, characterized by a harsh climate. Analysis of climate change for the period 1970-2020 was made on the basis of meteorological data from the open database of the All-Russian Research Institute of Hydrometeorological Information – the World Data Center[1] and the archive of observations of the Marre-Sale weather station.

Climate warming has been observed since the beginning of the 1970s (Fig. 2). Compared with 1961-1990, the mean annual air temperature (MAAT) has increased by 5.9°C, the mean annual temperature amplitude has decreased by 5.2°C. Its decrease depends on the rapid increase in the average winter temperature by 7.3°C. The mean summer air temperature is characterized by a less pronounced warming of 4.1°C. The greatest amount of precipitation falls

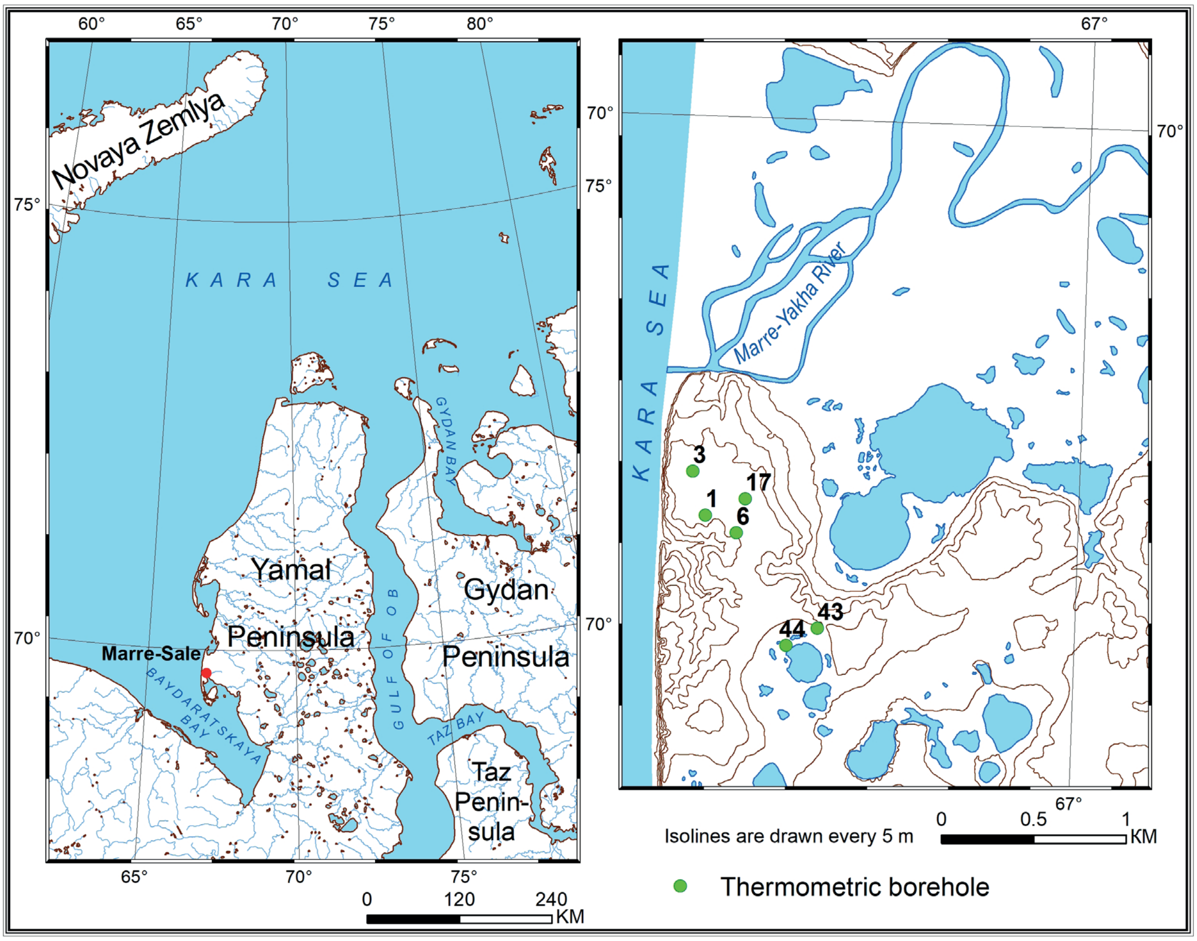

Fig. 1. Location of the study area and observation boreholes

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[1] http://meteo.ru/data/, accessed 14.11.2021

Table 1. Conditions for the permafrost temperature regime monitoring within one geomorphological level (IIIrd marine terrace)

Landscape	Monitoring site ID (borehole)
Dry landscapes	
Sand fields (6)*	43
Well-drained flat tundra (24)	6
Moist landscapes	
Wet tundra (7)	1
Wet landscapes	
Polygonal saturated tundra (17)	3
Water tracks and gullies (3)	Not observed
Flooded landscapes	
Lake basins (20)	44
Peatlands (4)	17

*The proportion of landscapes is given in parentheses, in % of the total area (Landscapes of permafrost …, 1983).

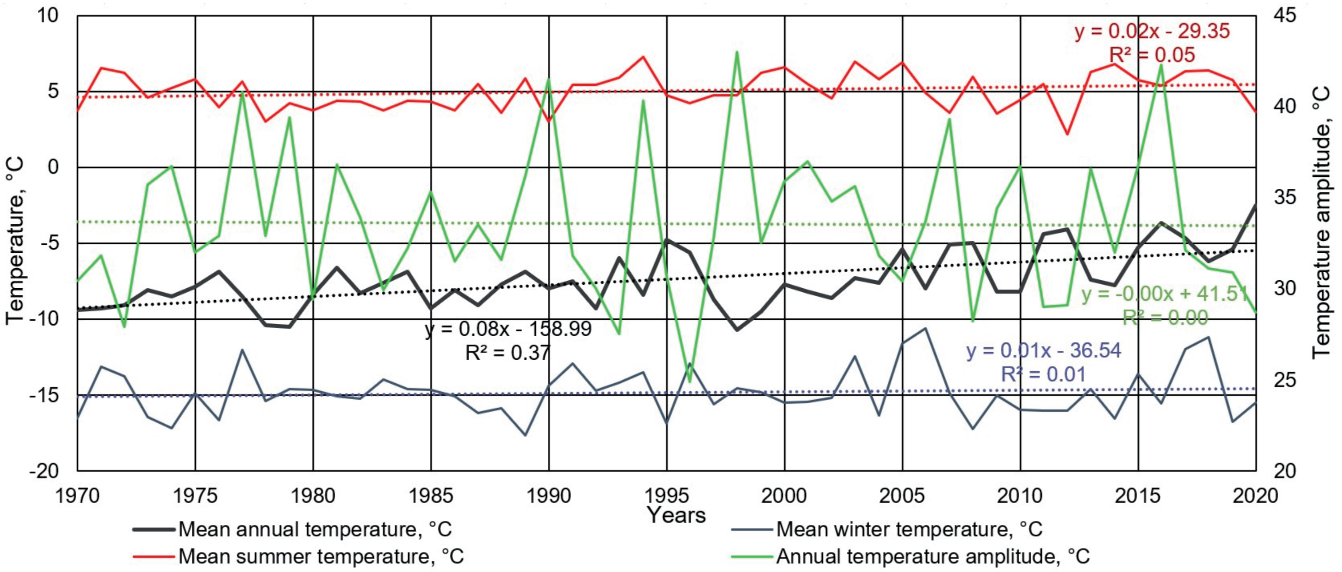

Fig. 2. Changes in the main meteorological parameters in Western Yamal (1970-2020). Dotted lines show linear trends

in the summer-autumn transitional period, mainly in August-September. Since 1970, total precipitation value has increased by 105 mm from 297 mm standard amount of annual precipitation (averaged over 1961–1990). For all months (except December), the average monthly temperature increase was observed during the specified period.

The maximum snow depth per season (the highest value of 3 snow stakes) had been increased from 16 to 49 cm from 1970 to 2020. Snow density ranges from 0.22 g/cm^3 in autumn to 0.45 g/cm^3 in spring, with an average per season of 0.32 g/cm^3. Table 2 summarizes the results of our observations of snow distribution over landscapes in comparison with the data on the weather station site. Observations were carried out from 1984 to 1992 every 10 days, starting from the day a stable snow cover was established to the day the snow cover began to break – the end of April. For each measurement, the ratio of snow depth on a particular landscape to one at the weather station site was found. Then, for each landscape, we calculated the average ratio for the entire time of snow accumulation. Observations of the spatial distribution of snow cover showed that each landscape type is characterized by a more or less stable ratio of snow height in dominant landscapes compared with the weather station site – the individual coefficient of snow accumulation (Table 2).

Table 2. Snow accumulation coefficient in monitoring sites

	Site ID (borehole)					
	1	3	6	17	43	44
Snow accumulation coefficient (ratio of snow depth near borehole to snow height at the weather station)	1.0	0.86	1.03	0.87	0.86	1.32

Methods

The study of the permafrost temperature regime at the geocryological research station was carried out in specially equipped boreholes with a depth of 10 m. The boreholes were drilled in 1978, drilling was accompanied by a detailed description and sampling of the core. The boreholes are protected by a casing pipe within the mean annual ALT, additionally buried in the frozen ground at 1 m depth. The upper part of the pipe, protruding 0.2 m above the day surface, is filled with heat-insulating materials (peat or foam insulation). The inlet of the pipe is tightly closed with a lid that prevents precipitation and condensate from entering the well.

At the time of drilling, the moisture content (ice content) of permafrost and active layer was determined. Since 2016, the sampling and determination of moisture/ice content of the active layer and the upper permafrost horizon has been carried out annually at the end of the warm season by drilling other boreholes at a certain site.

In 1978-1990 temperature measurements were carried out by the Russian Institute of Hydrogeology and Engineering Geology every ten days, and after 1990 once a year at the end of the warm period using soil thermometers (Pavlov, 1997). Thermometers were installed at depths of 0.5; 1 m and further every meter. Measurement accuracy was ±0.1°C. Since 1996, measurements in wells have been carried out by the Earth's Cryosphere Institute, Tyumen Scientific Center SB RAS. In 2006, four-channel data loggers HOBO U12-008 with thermistor sensors with a measurement accuracy of ±0.2°C were installed. The sensors are installed at depths of 0.02; 2; 3; 5 and 10 (12) m. Readings at a depth of 0.02 m correspond to the temperature under vegetation. In the well ID 1, additional loggers were installed at the depths of 4; 6 and 8 m. Temperature measurement is made every 6 hours.

RESULTS

Mean annual permafrost temperature

The mean annual temperature of the permafrost, determined at the level of zero annual amplitude, increased in all observed landscapes from 1978 to 2021 (Fig. 3).

Two groups of landscapes can be distinguished according to the mean annual permafrost temperature values. The first group includes "cold" landscapes of flat and polygonal tundra, confined to positive landforms. Here, the average annual temperatures in 1978-79 were -5.8…-7.4°C, and by 2021 they reached -3.7…-5.2°C. The "warm" landscapes of the second group with comparatively high mean annual permafrost temperatures include wet or flooded landscapes of lake basins and water tracks; river floodplain also belongs to this landscape group. The average annual temperatures had been increasing there from -4.2°C in 1978 to up to -2.7…-3.6°C in 1996-2002. Such a stable difference in temperatures of the two groups is explained by increased snow accumulation in negative landforms. The lowest temperatures are characteristic of polygonal and well-drained flat tundra (boreholes 3 and 6, respectively), and the highest temperatures are characteristic of lake basins (borehole 44). During 1978-2021 the average temperature increase in the landscapes of the first group was approximately 2.2°C, and in the second group – 1.5°C.

Following the change in air temperature, the change in the mean annual temperature of the permafrost was uneven over time. Positive deviations from the linear trend were observed in 1985 and 1996, and negative deviations in 1989 and 2001. Since 2007, the temperature has risen evenly in all observed landscapes.

Thus, under conditions of climate warming, landscapes of a typical tundra have a different response to warming, expressed in the mean annual temperature of the permafrost.

Annual temperature amplitude at 5 m depth

The shifting of permafrost thermal regime is not limited to an increase in the mean annual temperature. To study the effect of climate warming on permafrost thermal regime, the change in the annual temperature amplitude at the depth of 5 m was considered. The depth of 5 m is not special and was chosen for analysis because surface effects are already insignificant here, but all the features of the formation of the temperature amplitude are well reflected. As an example, Figure 4 shows the temporal changes of the permafrost temperature at a depth of 5 m in borehole

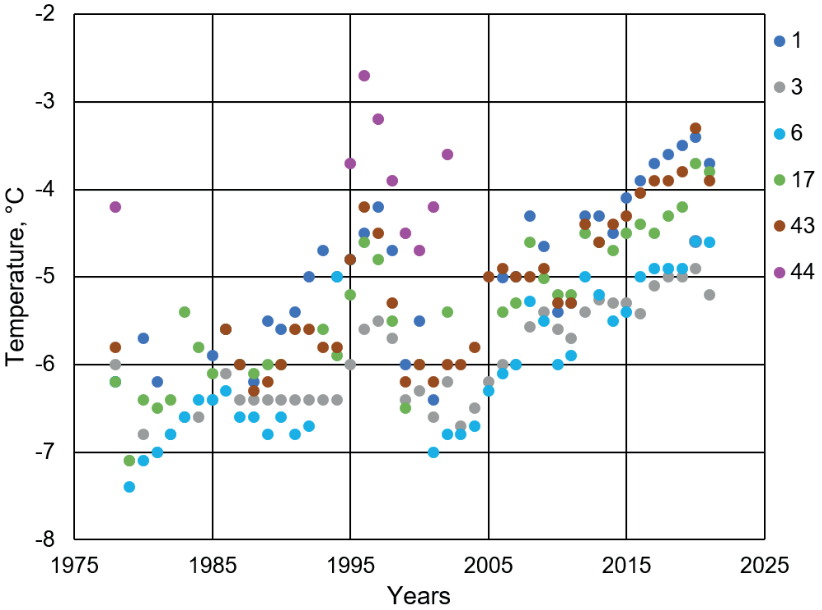

Fig. 3. Changes in the mean annual temperature of permafrost in dominant landscapes. The legend contains the site ID (borehole)

1, located in the wet tundra landscape. The situation is similar in all the studied landscapes.

Figure 5 shows the change in the amplitude of permafrost temperature fluctuations at the depth of 5 m over time. There is a clear downward trend in the amplitude of annual fluctuations in time for all the landscapes. The almost synchronous reduction occurs mainly due to the increase in winter temperatures, which has accelerated since the beginning of the century. The strongest reduction in the amplitude occurred in dry landscapes; in moistened and wet areas the reduction was less pronounced.

In addition to air temperature, the amplitude of annual permafrost temperature fluctuations is most affected by the height of the snow cover and the humidity (ice content) of the soils of the active layer due to the extra energy necessary to phase transitions of water in the active layer.

The relationship between the values of the annual temperature amplitude at the depth of 5 m and the maximum snow depth was studied, taking into account the conversion factors. As at the key site the snow depth increases with climate warming (Oblogov et al., 2020), the amplitude of permafrost temperature fluctuations rapidly decreases (Fig. 6). This trend is most pronounced within wet tundra, and least pronounced within dry tundra and sand fields. With a power-law approximation, the radius of correlation between the amplitudes and snow depth for drained tundra is $R^2 = 0.37$.

Soil moisture measurements in active layer were carried out in 1978 during boreholes drilling and in 2016-2021. This made it possible to estimate the change in the weighted average water content in the active layer of various landscapes over time. In the water tracks, with an increase in permafrost temperature by an average of 1.5°C, the moisture content of the active layer remained unchanged, close to full water saturation. In the rest of the landscapes, characterized by a more pronounced increase in the mean annual permafrost temperature, the average weight humidity changed from 20-23% (1978) to 24-27% (2021).

The depth of zero annual ground temperature amplitude

The established decrease in the amplitude of temperature fluctuations causes a decrease in the depth of the bottom of the layer of annual heat exchanges. It is

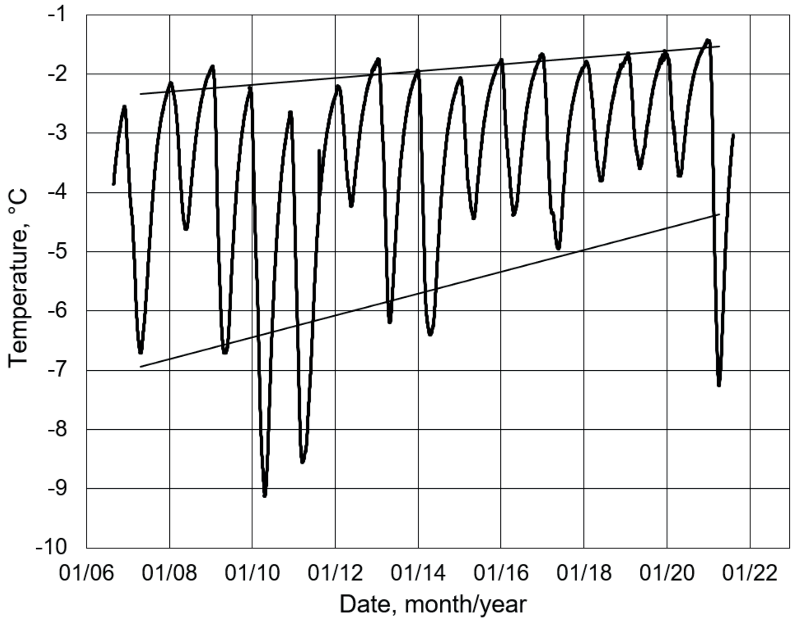

Fig. 4. Time course of permafrost temperature at the depth of 5 m in borehole 1 (wet tundra)

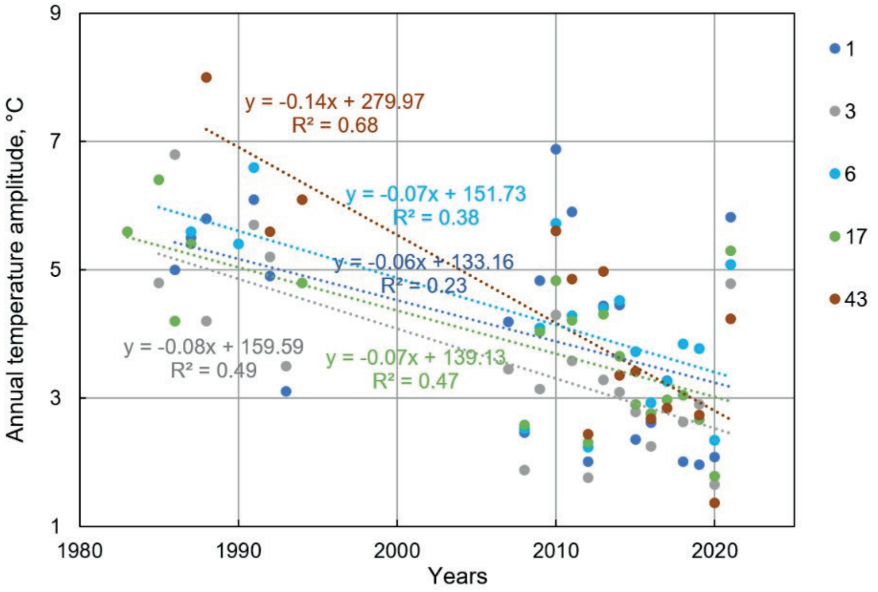

Fig. 5. Change in the annual ground temperature amplitude at a depth of 5 m in time. The legend contains the site ID (borehole). Dotted lines show linear trends

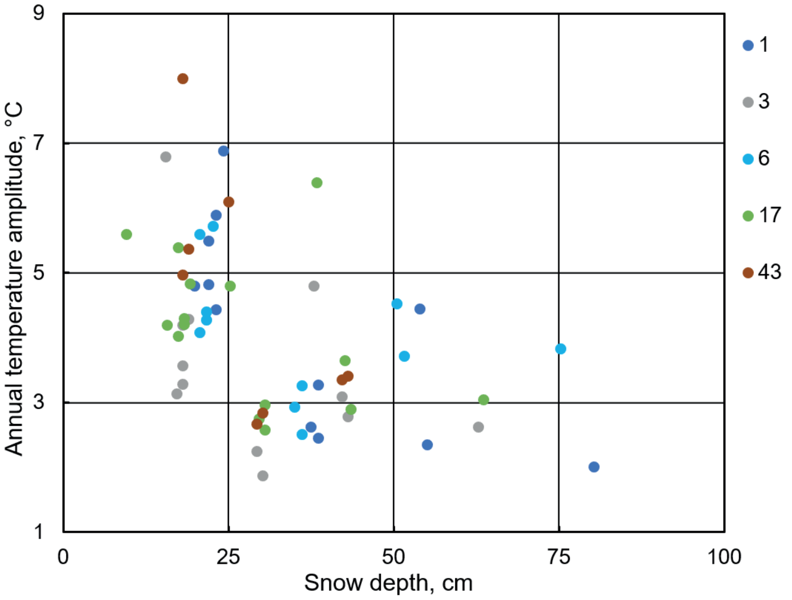

Fig. 6. Dependence of the annual ground temperature amplitude at the 5 m depth on the snow cover thickness. The legend contains the site ID (borehole)

determined by the boundary below which the difference in annual temperature fluctuations does not exceed 0.2°C. Given that the depth of the layer of annual heat transfers exceeds the depth of the boreholes, the level of zero annual amplitude is obtained by extrapolating the temperature curves down the section. The depth of zero annual amplitude decreased in all landscapes (Fig. 7). The most intense decrease is characteristic of the polygonal tundra (borehole 3), the least – for flat-topped peatlands (borehole 17).

DISCUSSION

Direct monitoring measurements of frozen ground temperature in 10 to 12-m deep boreholes conducted in Western Yamal since 1978 showed how the thermal state of permafrost is changing in various landscapes under the conditions of climate warming.

The mean annual permafrost temperature increased both in the initially "cold" landscapes located on positive landforms and in "warm" landscapes located in topographic lows and characterized by higher ground temperatures due to the influence of increased snow accumulation. Due to the increase in winter air temperatures, the amplitude of annual temperature fluctuations in permafrost, primarily in drained landscapes, also decreased. This led to a general decrease in the depth of zero annual temperature amplitude.

A pronounced reduction in the depth of zero annual amplitude over the past 40 years is observed all around the western Russian Arctic both in discontinuous and continuous permafrost zones (Malkova et al., 2022). The studied key site is northernmost in Western Russian Arctic among the areas with long-term permafrost monitoring. It is characterized by lower temperatures compared to the sites in discontinuous permafrost zone (Vasiliev et al., 2020). On the contrary, the rates of permafrost temperature rise here are higher compared to more southern regions, where permafrost temperatures are close to zero and latent heat effects related to melting ground ice becomes important (Romanovsky et al., 2018; Vasiliev et al., 2020).

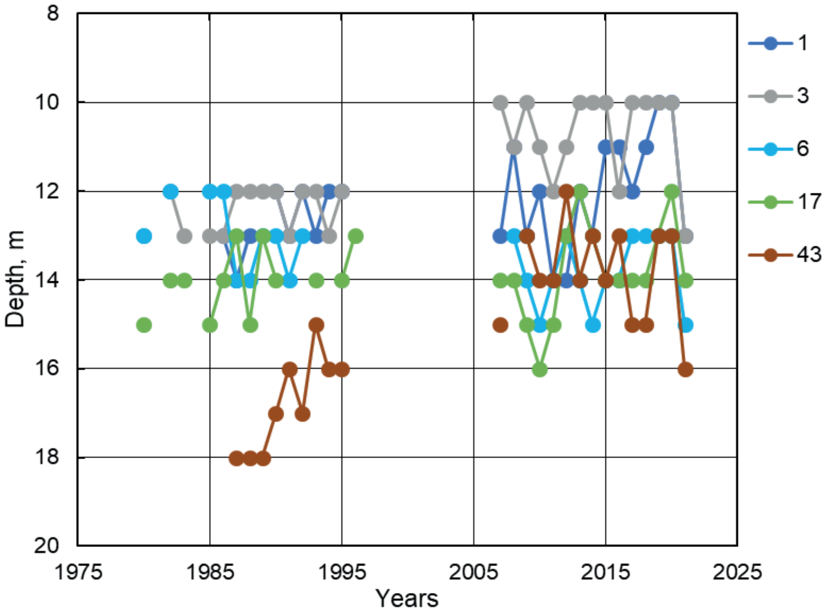

Fig. 7. Change in the depth of zero annual amplitude in time. The legend contains the site ID (borehole)

Currently, the permafrost of the Marre-Sale area is at the initial stage of degradation (Vasiliev, 2020) and is characterized by relatively low ground temperatures and increasing ALT. Further air temperature rise will lead to the next, metastable stage of permafrost degradation when thawing of the transient layer at the permafrost top occurs and the depth of permafrost table increases. Such a situation is observed now at monitoring sites situated more than 150 km south mostly in sporadic, discontinuous and continuous permafrost zones – Kumja, Kape Bolvanskiy, Vorkuta and north of Novy Urengoy (Vasiliev et al., 2020; Malkova et al., 2022). This transition to the next permafrost degradation stage will not occur simultaneously within different landscapes of the Marre-Sale area.

CONCLUSIONS

1. Climate warming in Western Yamal began in the 1970s and continues now. The mean annual air temperature has increased by 6.9°C (from -9.4°C in 1970 to -2.5°C in 2020), while the mean winter temperature is rising faster than the summer temperature. An increase in the mean annual air temperature is accompanied by an increase in the annual precipitation by 100 mm, the height of the snow cover has increased from 16 to 49 cm.

2. For 40 years of observations, the mean annual temperature of the permafrost increased by 1.5-2.2°C. At the same time, the maximum increase in the mean annual temperature is observed in the landscapes of flat and polygonal tundra associated with positive landforms.

3. Climate warming leads to a decrease in the amplitude of annual permafrost temperature fluctuations. The reduction in amplitude at a depth of 5 m was by 0.5-3.6°C in 1983-2021. The main reasons for this are the faster increase in air temperature in the cold period compared to the warm period, an increase in the height of the snow cover, and an increase in soil moisture in the active layer.

4. There is a tendency to reduction of the depth of the zero annual temperature amplitude from 12-18 m (1980) to 13-16 m (2021).

Thus, climate warming in the last 50 years has led to a significant change in the thermal regime of the permafrost – an increase in the mean annual temperature of the permafrost, a reduction in the amplitude of annual ground temperature fluctuations, and a decrease of the depth of zero annual amplitude. At the same time, despite noticeable climatic changes, the permafrost generally retains a stable state. ■

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