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PERMAFROST DEGRADATION: RESULTS OF THE LONG-TERM GEOCRYOLOGICAL MONITORING IN THE WESTERN SECTOR OF RUSSIAN ARCTIC

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The results of a long-term permafrost monitoring, which have been obtained at eight permafrost stations in the western sector of Russian Arctic, are presented. Increase in mean annual air temperatures in this area has reached approximately 2.8 °C (1970–2018). The data on mean annual ground temperature dynamics have been obtained for the active layer and upper permafrost for dominant landscapes of various bioclimatic zones: typical tundra, southern tundra, forest tundra, and northern taiga. Three stages of permafrost stability under the warming climate were determined: stable permafrost, unstable permafrost, and actively degrading permafrost. It was shown that permafrost degradation leads to active development of vegetation and migration of the boundaries of bioclimatic zones 30 to 40 km towards the north (1975–2018).

Permafrost, ground temperatures, long-term monitoring, permafrost stations, permafrost degradation, intermediate layer

INTRODUCTION

In recent decades, the problem of permafrost degradation due to climate warming in the Arctic has become a priority. Permafrost plays an important role in global climate change, the balance of greenhouse gases, changes in Arctic ecosystems, and land management in the Arctic regions [*Nelson et al., 2001; Hinzman et al., 2005; Romanovsky et al., 2010; AMAP, 2011; IPCC, 2013*]. Climate warming in the western sector of the Russian Arctic has been recorded since 1970. In this area, an increase in air temperature, duration of the warm period, a change in the amount of precipitation, and an increase in the thickness of the snow cover have been observed [*Pavlov, Malkova, 2005*].

As a result of the complex effect of climatic factors on the permafrost in the last 40–50 years, the temperature of permafrost has increased, and the thickness of the active layer has increased as well [*Pavlov, 1997; Osterkamp, Romanovsky, 1999; Romanovsky, 2006; Oberman, 2008; Vasiliev et al., 2008; Smith et al., 2010; Vasil'chuk, Vasil'chuk, 2015a,b; Streletskiy et al., 2015a; Kaverin et al., 2017; Boike et al., 2018; Biskaborn et al., 2019*]. Near the southern boundary of the permafrost, the area underlain by permafrost is likely to decrease, and lowering of the permafrost table currently occurs [*Streletskiy et al., 2015b*].

Prediction of changes in the permafrost characteristics has been recently improved due to elaboration of new methods of climate modeling and development of global and regional climate models. Climate models describe the dynamics and spatial distribution of climatic characteristics over the coming decades relatively well. Based on existing climate models, global and regional estimates of changes in permafrost characteristics have been made [*Anisimov et al., 2003; Nicolsky, Romanovsky, 2018*]. Romanovsky and his coauthors presented small-scale maps of the predicted changes in the mean annual temperature of the active layer that are expected by 2050 and 2100 [*Romanovsky et al., 2008*]. These maps show a wide band along the southern boundary of permafrost where permafrost thawing from above is expected.

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Shur and Jorgenson [*2007*] considered possible ways of permafrost degradation due to climate warming and human-induced surface disturbances. They noted that vertical and lateral degradation of permafrost is possible as a result of its reaction on both climatic and non-climatic impacts.

Thus, we can conclude that permafrost response to climatic changes is described in the scientific literature mainly based on estimates and calculations, while there is a significant lack of real observations of permafrost degradation in various bioclimatic zones.

Until now, there is no scientific consent on what changes in permafrost can be attributed to its degradation: only its transition from frozen state to unfrozen caused by increase in the mean annual temperature of permafrost [*Paffengolz et al., 1973*], or reduction in cold resources in permafrost caused by natural and anthropogenic impacts that lead to decrease in the area of permafrost distribution, increase in temperature, and decrease in the thickness of permafrost, which may eventually lead to its disappearance [*Baulin, Murzaeva, 2003*].

Following Burn [*2004*], we consider that permafrost is degrading if at least within some part of permafrost sequence (usually the upper one) mean annual ground temperatures have become positive. In this work, we focus on the most critical case of permafrost degradation, when continuing thawing of the upper horizon of permafrost and lowering of the permafrost table are observed.

STUDY AREA

The dynamics of permafrost under changing climate have been monitored at eight permafrost stations located within all major bioclimatic zones of the western sector of the Russian Arctic – from typical tundra to northern taiga (Fig. 1).

The boundaries of bioclimatic zones were determined when in a circumpolar map of vegetation [*Walker et al., 2009*]. Studies of the permafrost thermal regime have been performed in boreholes located in all dominant landscapes characterizing the territory adjacent to the station area in undisturbed conditions, except two boreholes of the South Urengoy station. In 2003–2006, observations of the permafrost temperature in boreholes were included in the GTN-P program (Global Terrestrial Network for Permafrost) [*Biskaborn et al., 2015*]. At all permafrost monitoring stations, observations of the active layer thickness have been performed at previously established grids according to the CALM protocol (Circumpolar Active Layer Monitoring) [*Brown et al., 2000*].

Marre-Sale Station. The permafrost monitoring station is located in the typical tundra zone on the west coast of the Yamal Peninsula, near the weather station of the same name. The vegetation cover consists mainly of shrubs, mosses, and lichens. The region belongs to the continuous permafrost zone. Observations of the thermal regime of permafrost were performed in five 10-m-deep boreholes located in dominant landscapes on the surface of the third marine terrace (1978–2018) and in one borehole on the tidal flats (1978–2001). The elevations of the surface of the third marine terrace are 20 to 30 m a.s.l., and of the tidal flats are 2.5 m a.s.l. In 1995, the CALM grid was established, where the active layer thickness have been measured annually, and the thermal regime of permafrost has been studied to a depth of 2.0 m. Climate data were obtained from the Marre-Sale weather station.

Cape Bolvanskiy Station. The permafrost station is located on the Barents Sea coast close to the Pechora River delta in the southern tundra zone. The vegetation cover consists mainly of shrubs, mosses, and lichens. This area belongs to the continuous permafrost zone. The CALM grid was established here in 1999. Observations of the thermal regime have been performed in six boreholes 10 to 12 m deep, located nearby on the surface of the third marine terrace with elevations of 24 to 30 m a.s.l., as well as in the active layer at the CALM grid. Observations covered all dominant landscapes. To analyze climatic fluctuations, we used the data obtained from the Cape Konstantinovskiy weather station, located at a distance of about 50 km northeast of the station.

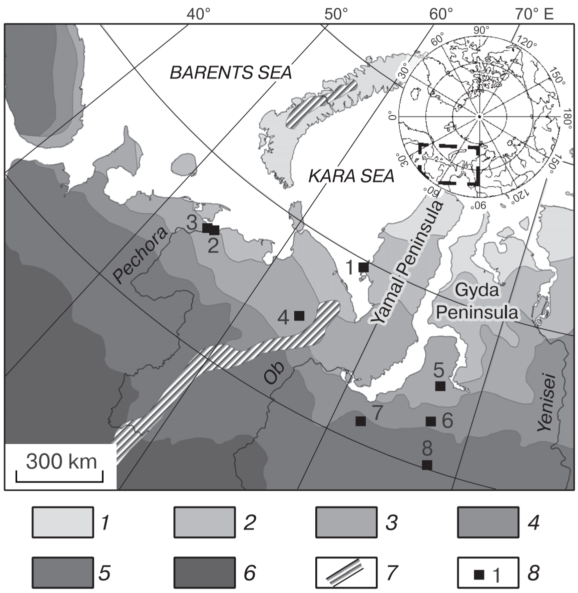

Fig. 1. Location of permafrost monitoring stations in different bioclimatic zones of the western sector of Russian Arctic.

1 – northern (arctic) tundra; *2* – typical tundra; *3* – southern tundra; *4* – forest tundra; *5* – northern taiga; *6* – typical taiga; *7* – mountain permafrost; *8* – numbers of stations: 1 – Marre-Sale, 2 – Cape Bolvanskiy, 3 – Kumzha, 4 – Vorkuta, 5 – Severniy (North) Urengoy, 6 – Yuzhniy (South) Urengoy, 7 – Nadym, 8 – Tarko-Sale.

Table 1. **Metadata for borehole monitoring in the western sector of Russian Arctic**

Monitoring station, coordinates	Bioclimatic zone	Permafrost extent	Boreholes, observation period (years)	B-hole depth, m	Landscape, surface conditions	Vegetation cover	Soil texture
Marre-Sale (Western Yamal), 69°43′ N, 66°49′ E	Typical tundra	Continuous	1 (1978–2018)	10	Damp tundra	Shrub-Moss-Lichen	Silt
			3 (1978–2018)	10	Wet tundra	Shrub-Lichen-Moss	Silt, sand
			6 (1978–2018)	10	Well-drained tundra	Shrub-Moss-Lichen	Silt, sand
			17 (1979–2018)	10	Peatland	Shrub-Lichen-Moss	Peat up to 1.6 m, silt
			36 (1978–2001)	10	Tidal flat, bog	Sedge-Moss	Peat up to 0.3 m, sand
			43a (1978–2018)	10	Sandy blowout	No vegetation	Sand
Cape Bolvanskiy, 68°17′ N, 54°30′ E	Southern tundra	Continuous	54 (1983–1993, 1999–2018)	12	Moist tundra	Moss-Lichen	Sand, silt, and silty clay interbedding
			55 (1983–1993, 1999–2018)	10	Polygonal peatland	Moss-Lichen	Peat up to 4 m, underlain by silty clay
			56 (1983–1993, 1999–2018)	10	Peatland	Moss-Lichen	Peat up to 2 m, underlain by silty clay
			59 (1983–1993, 1999–2016)	12	Well-drained tundra	Lichen-Moss with frost boils	Silty clay with gravel
			65 (1983–1993, 1999–2018)	12	Moist tundra	Moss-Lichen	Sand and silty clay interbedding
			83 (1983–1993, 1999–2016)	10	Well-drained tundra	Lichen-Moss	Silt and silty clay interbedding
Kumzha, 68°11′ N, 53°47′ E	Southern shrub tundra	Sporadic	3 Ku (2016–2018)	6	Well-drained shrub tundra	Shrub-Lichen-Moss	Sand with gravel
Vorkuta, 67°35′ N, 64°10′ E	Southern tundra	Discontinuous	CALM R2 (1999–2017)	0.5	Damp tundra	Moss-Shrub	Silty clay
Severniy (Northern) Urengoy, 67°28′ N, 76°42′ E	Southern tundra	Continuous	15-03 (1975–2018)	10	Damp flat river valley bottom	Shrub-Moss with sporadic peatlands and bogs	Silty clay
			15-06 (1975–2018)	10	Drained erosion-talus slope	Willow and alder up to 2.5 m high with grass	Silt, silty clay
			15-08 (1975–2018)	10	Drained hilltop	Shrub-Moss	Silty clay
			15-20 (1975–2018)	10	Drained hilltop	Shrub-Moss	Silty clay
Yuzhniy (Southern) Urengoy, 66°19′ N, 76°54′ E	Forest tundra	Discontinuous	5-01 (1975–2018)	10	Drained slope	Clear-cut larch forest with shrubs up to 1.5 m	Silt, silty clay
			5-03 (1975–2018)	10	Top of palsa	Sporadic undergrowth of birch and larch	Silt, silty clay
			5-07 (1975–2018)	10	Boggy water track	Shrubby mounds and tussocks divided by small grassy bogs	Peat up to 1 m, silty clay
			5-08 (1977–2010)	10	Well-drained slope	Larch forest	Sand
			5-09 (1975–2018)	10	Disturbed surface	Burnt birch forest with undergrowth of shrub and birch	Sand
			5-10 (1977–2018)	10	Drained slope	Larch forest	Sand, silt
Nadym, 65°18′ N, 72°51′ E	Northern taiga	Sporadic	11-75 (1975–2018)	10	Large-mound peatland	Grass-Shrub-Moss-Lichen	Peat up to 1 m, sand
			14-72 (1972–2018)	10	Flat-mound peatland	Grass-Shrub-Moss-Lichen	Peat up to 0.5 m, sand
			23-75 (1975–2018)	10	Bog	Shrub-Grass-Moss	Peat up to 0.5 m, sand, silty clay
			1-71 (1971–2018)	10	Lithalsa	Grass-Shrub-Moss-Lichen	Peat up to 0.3 m, sand
Tarko-Sale, 65°02′ N, 77°30′ E	Northern taiga	Isolated	1 T-S (2006–2019)	30	Flat-mound peatland	Shrub-Moss-Lichen	Peat, sand, silt, clay
			2 T-S (2006–2019)	30	Drained ridge	Coniferous undergrowth with shrubs	Peat, sand, silty clay, clay

Kumzha Station. The permafrost station is located in the Pechora River delta in the southern tundra zone, 32 km south-west of Bolvanskiy station. The vegetation cover is represented by moss-lichen communities; shrubs are common in depressions. The site is located within the remnant of the first alluvial terrace with elevations of 5 to 8 m, surrounded by the channels of the Pechora River. This area belongs to the sporadic permafrost zone. Permafrost table is dome shaped and lies at a depth from the surface ranged from 2.6 m (in the center of the remnant) to 7.1 m (in its marginal parts). The CALM grid was established in 2016 in the central part of the remnant. To monitor dynamics of the depth to the permafrost table at this site, in addition to directly measuring with the permafrost probe along the established profiles, seismic and ground-penetrating radar (GPR) surveys have been performed annually [*Sadurtdinov et al., 2018*]. To study permafrost structure and thermal regime, three boreholes were drilled in 2016; temperature of the active layer has been monitored in two boreholes, and a third borehole (No. 3 Ku) has been used to monitor the thermal regime of permafrost.

Vorkuta Station. Data on permafrost dynamics at this station are presented here based on the study by Kaverin et al. [*2017*]. The CALM grid in this area was established in 1999, about 13 km to the northwest of the city of Vorkuta. At this grid, a full cycle of observations of thaw depths and thermal regime of the active layer has been performed annually. This area belongs to the discontinuous permafrost zone. The site is represented by shrub-moss tundra with numerous frost boils at various stages of vegetation development. Dwarf birch and willow up to 50 cm high are observed in this area [*Mazhitova et al., 2004*]. Climatic data were obtained from the Vorkuta weather station.

Severniy (North) Urengoy Station. The permafrost station is located about 180 km north of the city of Noviy Urengoy in the southern tundra zone. The vegetation cover is represented mainly by shrub-grass-moss communities within gentle hills and grass-moss communities in hasyreys (thaw-lake basins) and depressions. The area is located within the continuous permafrost zone. Observations of the thermal regime of permafrost have been performed since 1975 in four boreholes located in dominant landscapes on the third marine terrace with elevations 30 to 35 m a.s.l. The CALM grid was established in 2008, but the thermal regime of the active layer has not been studied. To analyze climatic fluctuations, we used the data obtained from the Noviy Urengoy weather station.

Yuzhniy (South) Urengoy Station. The permafrost station is located about 30 km north of the city of Noviy Urengoy in the forest-tundra zone, on the surface of the fourth lacustrine-alluvial plain with elevation of 60 to 70 m a.s.l. The vegetation is represented by poorly developed woodlands with larch-birch-lichen communities. Shrub-moss communities are common within peat bogs and tundra areas, and shrubs are common in gullies and depressions. Frost mounds are covered with sparse forests. The region belongs to the discontinuous permafrost zone. Observations of the thermal regime of permafrost started in 1975 in five boreholes. Boreholes 5-01 and 5-09 are located within landscapes with disturbed vegetation cover. In 2008, the CALM grid was established; however, observations of the thermal regime of the active layer have not been performed. Climatic characteristics were obtained from the data of the Noviy Urengoy weather station.

Nadym Station. The permafrost station is located 30 km from the city of Nadym in the northern taiga zone on the surface of the third lacustrine-alluvial terrace with elevations of 30 to 40 m a.s.l. The vegetation is represented by larch and birch sparse forest with grass-moss-lichen cover in combination with peat plateaus and flat bogs with shrub-moss-lichen cover. Peat and peat-mineral mounds are abundant. The area belongs to the sporadic permafrost zone. Permafrost occurs mainly within bogs, peatlands, and peat and peat-mineral frost mounds (palsas and lithalsas). Observations of the thermal regime of permafrost have been performed in four boreholes located on mounds and in a frozen bog. The CALM grid was established in 1995; active-layer thickness and temperature measurements have been performed here annually. Climate data were obtained from the Nadym weather station.

Tarko-Sale Station. The study of the thermal regime of the permafrost at this station has been performed since 2006 by employees of the Tyumen Industrial University. The station is located in the northern taiga, within the third lacustrine-alluvial terrace with elevations of about 34 m a.s.l. The vegetation is represented by larch and birch sparse forests with shrub-moss-lichen cover. The area belongs to the sporadic permafrost zone. Temperature measurements have been performed in three boreholes, two of which were drilled on a frost mound and a drained ridge. Observations under the CALM program started in 2018. Temperature measurements in the active layer have been performed to a depth of 1.0 m. Climate data were obtained from the Tarko-Sale weather station, located about 30 km from the station.

The characteristics of all boreholes, which provided the data that were used in this paper, are presented in Table 1.

OBSERVATION METHODS

At each permafrost monitoring station in all dominant landscapes, observations of the thermal regime of permafrost have been performed in boreholes with a depth of 10 to 12 m, which approximately corresponds to the depth of zero annual amplitude. At the Tarko-Sale station, the boreholes have a depth of 30 m.

All boreholes were drilled in various years (from 1975 to 2016) using the M-10 manual drill equipped with a small gasoline-powered engine with continuous collection of frozen cores. A detailed description of soil texture and cryostratigraphy of frozen deposits was made, along with sampling of frozen cores every 0.5 m to determine physical and chemical properties. The boreholes were equipped for long-term measurements of ground temperatures in accordance with the generally accepted methodology [*Grechishchev, Melnikov, 1989*].

Until 2003, temperature measurements in boreholes were performed using high-inertia thermometers. The standard installation depths for thermometers were 0.5, 1.0 m, and then every meter throughout the depth of boreholes. Measurements were taken every 10 days, and after 1990 once a year at the end of warm season. The accuracy of temperature measurements was ±0.1 °C. Thermometers located at the bottom of boreholes with a depth of 10 to 12 m showed the permafrost temperatures, which we considered to be the mean annual ground temperature even for a single measurement, because at this depth the ground temperatures practically do not experience seasonal fluctuations during the year. After 2003, 4-channel HOBO U12 loggers were installed in the boreholes. According to the GTN-P protocol [*Biskaborn et al., 2015*], the required sensor installation depths were 2, 3, 5, and 10 or 12 m. In some boreholes, two loggers were installed; in these cases, ground temperatures were measured at depths of 0.5, 1, 2, 3, 4, 5, 7, and 10 or 12 m. Measurements have been taken every 6 hours. HOBO U12 loggers provide accuracy of ±0.1 °C in measuring ground temperatures.

To measure soil temperature in the active layer, 2-channel HOBO Pro v2 loggers with measurement accuracy of ±0.1 °C were used. Depending on the thickness of the active layer, one or two loggers with sensors installed every 0.5 m were used.

A position of the permafrost table up to a depth of 2.0 m was detected using a steel permafrost probe. For depths of 2.0 to 3.5 m, manual drilling was used every 2 to 3 years. For greater depths of the permafrost table, seismic methods were used [*Melnikov et al., 2010*]. In sand sediments, GPR survey proved itself to be efficient for determining the permafrost table for depths of up to 10 m [*Sadurtdinov et al., 2018*]. GPR surveys have been used annually at the Kumzha site, and in 2018 they were also performed at the Nadym station. The determination of the permafrost table position with seismic methods in the areas of Yuzhniy (Southern) Urengoy, Severniy (Northern) Urengoy, and Nadym has been performed every 2 to 3 years. The accuracy of estimation of the permafrost table position is 0.3 m for seismic methods, and approximately 0.2 m for GPR surveys.

CLIMATIC CONDITIONS

According to climatic zoning of the Arctic [*Prik, 1971*], the western sector of the Russian Arctic belongs to the Atlantic sector of the Arctic Ocean. This area is heavily influenced by mid-latitude circulation processes, especially the Iceland Depression. Based on climatic features, this area is divided into three zones. The northern tundra of the Yamal Peninsula and the Gydan Peninsula is characterized by marine Arctic climate. The typical and southern tundra of the European North, the central and southern parts of Yamal, and the Gydan and Taz Peninsulas belong to the zone with marine subarctic climate. The southern part of this area (forest-tundra and northern taiga) are characterized by temperate continental climate.

Main characteristic feature of the climate of the western sector of the Russian Arctic is an increase in the severity of the climate from west to east. According to the data of the Arkhangelsk weather station (64°30′ N, 40°44′ E), the mean annual air temperature in the western part of the region is 0.8 °C, while in the eastern part, according to the Dikson weather station (73°30′ N, 80°24′ E), it drops to –11.8 °C.

The current stage of climate warming in the western sector of the Russian Arctic began in the 1970s and has occurred synchronously throughout the entire region.

Monthly average climate characteristics were obtained from the websites [www.meteo.ru/data] and [www.rp5.ru]. Daily average characteristics were obtained from archives directly at the weather stations.

The change in the mean annual air temperature over time recorded at weather stations adjacent to permafrost monitoring station is shown in Fig. 2.

In general, an increase in mean annual temperature occurs synchronously with minor local fluctuations. From 1970 to 2018, the region's mean annual air temperature rose by approximately 2.8 °C, which is close to the "harsh" scenario of climate change [*IPCC, 2013*]. The minimum warming trend was 0.052 °C/year (Noviy Urengoy), the maximum 0.072 °C/year (Tarko-Sale). An analysis of spatial changes showed that from 1970 to 2018 a shift in the contours of the mean annual air temperature of approximately 80 to 100 km to the northeast has occurred [*Malkova et al., 2018*].

Analysis of data on annual precipitation shows that in the western sector of the Russian Arctic a slight increase of 1–3 mm/year occurred in 1970–2018. This value approximately corresponds to the projected estimates based on the use of the ensemble of 12 CMIP5 climate models [*Linderholm et al., 2018*]. Moreover, in the areas of Nadym and Urengoy with a temperate continental climate, the increase in the annual amount of precipitation is slightly larger than in areas with a temperate marine climate.

The formation of the thermal regime of permafrost is greatly affected by snow cover. Snow cover in

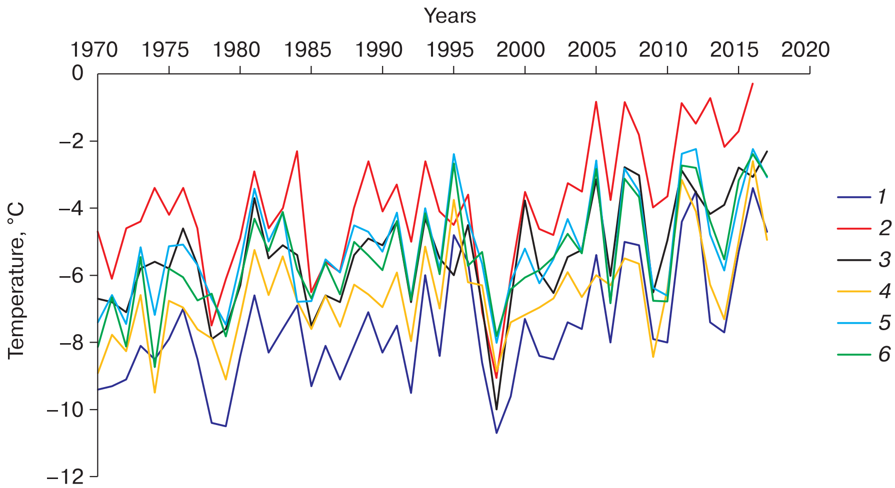

Fig. 2. Changes in mean annual air temperatures over time in the western sector of Russian Arctic.
1 – Marre-Sale; *2* – Cape Konstantinovskiy; *3* – Vorkuta; *4* – Noviy (New) Urengoy; *5* – Nadym; *6* – Tarko-Sale.

the study area begins to form in the first 10 days of October, reaches its maximum in April, and completely disappears by the end of May.

The greatest thickness of the snow cover is observed in the bioclimatic zones of forest-tundra and northern taiga. In Urengoy, its average value is approximately 114 cm, in Nadym – 85 cm, and in Tarko-Sale – about 90 cm. In the zones of typical and southern tundra, a thickness of the snow cover is much smaller: at Cape Bolvanskiy, average long-term thickness of the snow cover is about 58 cm, in Vorkuta – 44 cm, and in Marre-Sale – 33 cm. At all weather stations, an increase in the maximum thickness of the snow cover with time has been observed. Its greatest increase has occurred in the tundra zone, where the rate of increase in the maximum thickness of the snow cover reaches 1.8 cm/year (1998–2018), while in the zone of the forest-tundra and northern taiga this rate is 0.6 cm/year (2003–2018).

Discussion on the permafrost monitoring results

The results of long-term monitoring of the mean annual ground temperature at a depth of zero annual amplitudes are shown in Fig. 3. According to this figure, in all bioclimatic zones and dominant landscapes an increase in the mean annual ground temperature with warming climate has been observed. At the same time, the rate of increase in the mean annual ground temperature in various bioclimatic zones is not equal with an approximately equal increase in the mean annual air temperature of 2.8 °C, which corresponds to the average long-term climate warming trend of 0.06 °C/year (1970–2018).

The largest changes in the mean annual ground temperature have been observed in the zone of typical tundra. The average increase in ground temperature have reached 0.056 °C/year. Moreover, all landscapes are characterized by approximately the same reaction to climate warming. Despite a significant increase in the mean annual ground temperature, permafrost these days is characterized by low temperatures ranging from −3.5 to −5.0 °C, and its condition is still stable.

In the zone of southern tundra in the Northern (Severniy) Urengoy region, the rate of average increase in the mean annual ground temperature for various landscape conditions has been approximately 0.05 °C/year. This region includes landscapes with relatively high and low mean annual temperatures of permafrost. In "cold" landscapes with shrub-moss vegetation, the highest increase in mean annual temperature from −5.5 °C (1975) to −3.5 °C (2018) has been observed in well-drained areas (boreholes 15-03, 15-08, and 15-20). At the same time, within the well-drained "warm" areas with a high shrub vegetation (borehole 15-06), mean annual ground temperature has increased only by 1.0 °C: from −1.8 °C (1978) to −0.8 °C (2018).

The slow reaction of high-temperature permafrost to climate change is also typical of the southern tundra landscapes of the European North. Due to sectoral differences in climatic characteristics within the same landscape conditions, permafrost conditions observed in the European North of Russia have been warmer than in Western Siberia [*Drozdov et al., 2012*]. At the Bolvanskiy station, an average increase in mean annual ground temperatures for various landscapes was 0.04 °C/year. In 1980s, mean annual ground temperature at a depth of 10 m varied from −0.8 to −2.5 °C, and during the monitoring period it increased by 0.2 to 1.2 °C, while the range of variations in mean annual ground temperature in various landscapes has decreased almost threefold and tem-

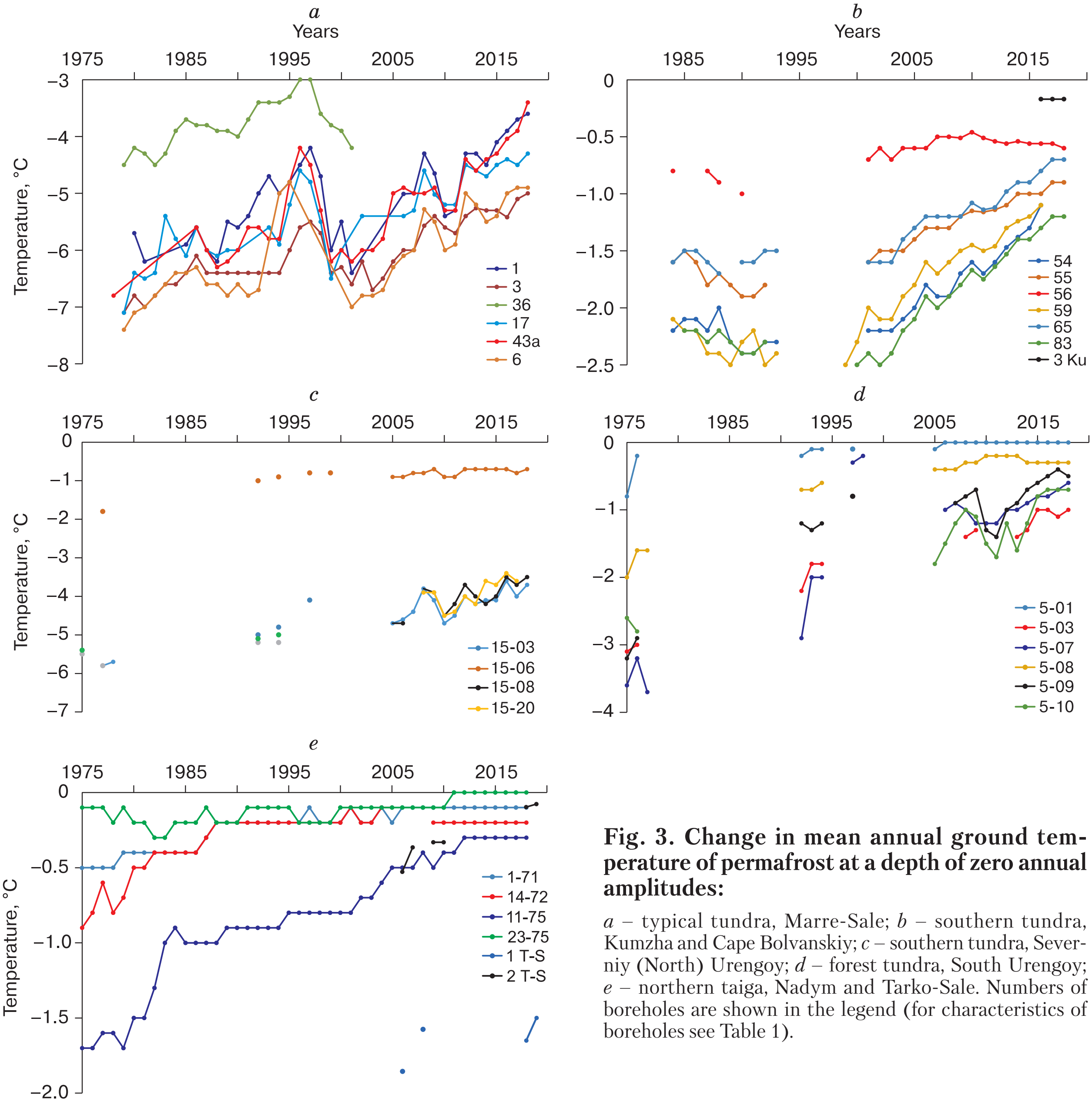

Fig. 3. Change in mean annual ground temperature of permafrost at a depth of zero annual amplitudes:

a – typical tundra, Marre-Sale; *b* – southern tundra, Kumzha and Cape Bolvanskiy; *c* – southern tundra, Severniy (North) Urengoy; *d* – forest tundra, South Urengoy; *e* – northern taiga, Nadym and Tarko-Sale. Numbers of boreholes are shown in the legend (for characteristics of boreholes see Table 1).

peratures currently vary from –0.6 to –1.2 °C [*Malkova et al., 2018*].

In the forest-tundra zone, in the area of Southern (Yuzhniy) Urengoy station, the rate of increase in the mean annual ground temperature in relatively "cold" sparsely forested landscapes (boreholes 5-03, 5-07, 5-08, and 5-09) was about 0.045 °C/year. In borehole 5-01, mean annual ground temperature, measured at a depth of 10 m, increased from –0.8 to 0 °C and by 2012 permafrost in the borehole area had completely thawed to a depth of 10 m. At the end of 1970s, after a forest was cut down here, the conditions of heat exchange changed abruptly, and progressive thawing of the permafrost from above began. A similar situation occurred in the area of borehole 5-08 located on a well-drained slope. Although deforestation did not occur here, permafrost began to thaw gradually from mid-1970s and thawed to a depth of 7 m by 2010. At the same time, mean annual ground temperature in borehole 5-08 at a depth of 10 m remained negative and fluctuated between –0.2 and –0.35 °C during the entire observation period.

In the northern taiga zone, at the Nadym station, mean annual ground temperature in peat mounds has increased from –1.7 to –0.3 °C, while within other landscapes it raised close to the thawing point and reached –0.2 to 0 °C by 2018. In this area, permafrost thawing has been observed in bogs where the depth of the permafrost table has reached approximately 4.0 m. At the Tarko-Sale station, mean annual ground temperature on the frost mound has increased from −1.9 to −1.6 °C (2006–2019), and on the drained ridge – from −0.6 to −0.1 °C, while the permafrost table has lowered to a depth of 6 m.

Thus, during the climate warming that has resulted in temperature increase of 2.8 °C (1970–2018), mean annual ground temperature still remains negative almost everywhere, except borehole 5-01 (South Urengoy), where the temperature has become positive but still close to 0 °C. In the areas of boreholes 23-75 (Nadym) and 2 T-S (Tarko-Sale), where mean annual ground temperature at a depth of 10 m has increased up to −0.1 °C, thawing of permafrost from above has been already observed. It means that mean annual ground temperature, measured at a depth of zero annual amplitudes, cannot characterize the physical state of the upper permafrost, whose uppermost horizons can be both frozen and unfrozen. This problem is related not to measurement errors but to the nature of distribution of mean annual ground temperatures with depth. Figure 4 shows the values of maximum, minimum, and mean annual ground temperatures in 2017 for two bioclimatic zones. In both cases, the distribution curves of mean annual ground temperature with depth show higher temperatures in the upper part of the section and indicate a tendency to warming that follows changes in temperature during the previous year.

In the typical tundra zone, mean annual ground temperature at a depth of 1.0 m was −3.14 °C, and at a depth of 10 m it was −3.7 °C. In the northern taiga zone it was +0.16 and −0.1 °C, correspondingly. In the first case, permafrost was overlain directly beneath the active layer. In the second case, mean annual ground temperature had positive values to a depth of 4.0 m, and, therefore, the permafrost table was lowered to this depth.

Thus, in conditions of climate warming, negative mean annual ground temperature, measured at a depth of zero annual amplitudes, does not guarantee the frozen state of the overlying deposits. We should also emphasize that within the same bioclimatic zone there may be landscapes with varying levels of resistance to climate change [*Vasiliev et al., 2008; Drozdov et al., 2012; Malkova et al., 2018*].

Permafrost thawing starts when mean annual ground temperature changes to positive values within any part of the permafrost sequence. With climate warming, such a transition is expected primarily in the upper horizons of permafrost [*Burn, 2004*]. Analysis of changes in mean annual ground temperatures in the active layer showed that in some cases such a transition has already occurred in the western sector of the Russian Arctic (Fig. 5). According to this figure, mean annual ground temperatures of the active layer since 2007 have had positive values at almost all permafrost monitoring stations except Marre-Sale (typical tundra). This means that soils of the active layer have already transformed from seasonally thawed to seasonally frozen state, i.e. permafrost degradation and transition of mean annual ground temperatures of the active layer to the positive values have already occurred. We should emphasize that this transition of the active layer from seasonally thawed to seasonally frozen state at the Cape Bolvanskiy station already occurred in 2010 while mean annual

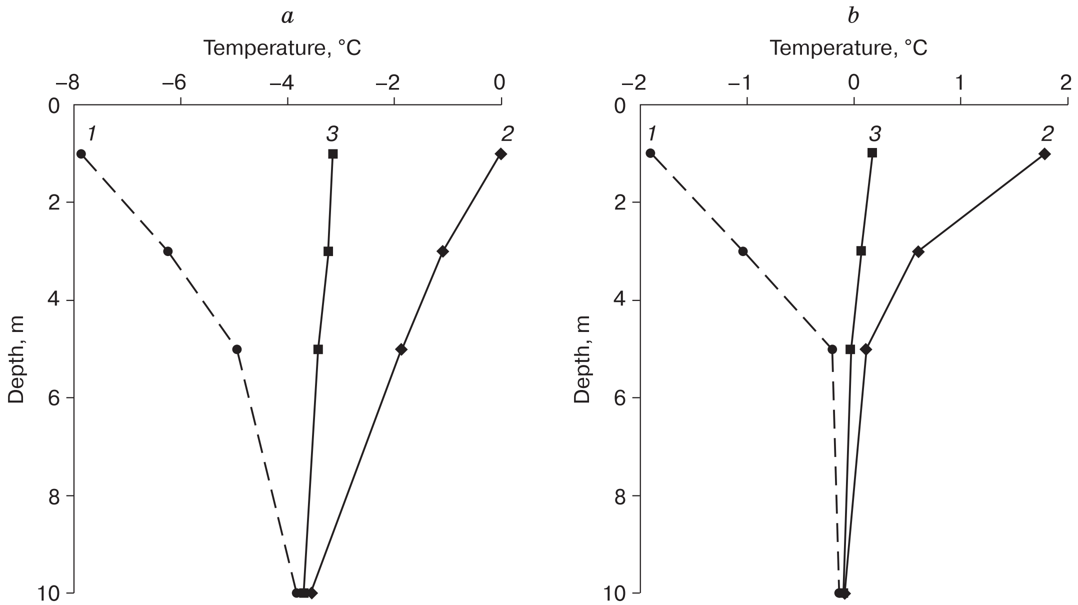

Fig. 4. Distribution of minimum (*1*), maximum (*2*), and mean annual ground (*3*) temperature with depth:
a – typical tundra, Marre-Sale; *b* – northern taiga, Nadym.

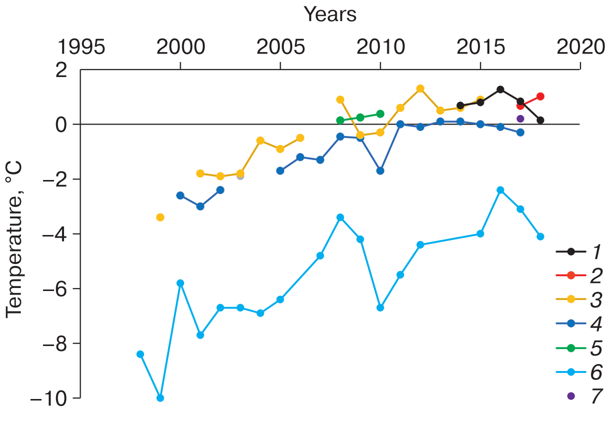

Fig. 5. Changes mean annual ground temperature of the active layer with time.

1 – Cape Bolvanskiy; *2* – Kumzha; *3* – Vorkuta; *4* – Nadym (measured at a depth of 0.85 m); *5* – Nadym (measured at a depth of 1.3 m); *6* – Marre-Sale; *7* – Tarko-Sale.

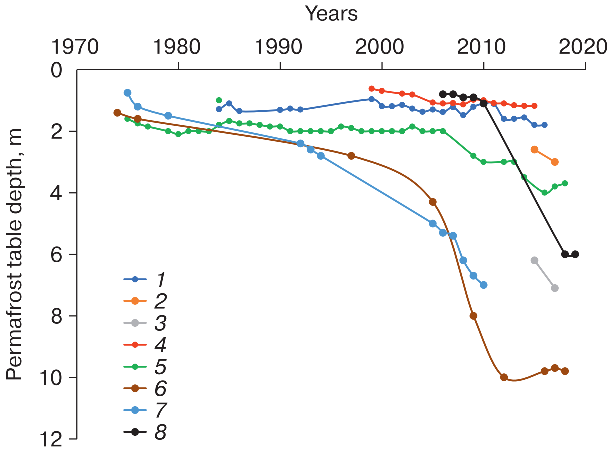

Fig. 6. Change in position of the permafrost table with time.

1 – Cape Bolvanskiy, borehole 59; *2* – Kumzha, borehole 3 Ku, the central part of the site; *3* – Kumzha, the marginal part of the site; *4* – Vorkuta; *5* – Nadym, borehole 23-75; *6* – Yuzhniy (South) Urengoy, borehole 5-01; *7* – Yuzhniy (South) Urengoy, borehole 5-08; *8* – Tarko-Sale, borehole 2 T-S.

ground temperature at a depth of 10 m was still −1.4 °C. At the Yuzhniy (South) Urengoy station, permafrost degradation and positive mean annual ground temperatures of the active layer were recorded in the early 1990s, while mean annual ground temperature of permafrost at a depth of 10 m was approximately −0.7 °C. Thus, degradation of the upper horizons of permafrost can start when mean annual ground temperatures at a depth of zero annual amplitudes are still relatively low.

Permafrost degradation is accompanied by lowering of its table. The results of observations are shown in Fig. 6. In the typical tundra zone, only an increase in seasonal thawing has been observed, but there is still no detachment of the permafrost table from the base of the active layer.

In the southern tundra zone, at the CALM grid of the Bolvanskiy monitoring station, the thickness of the seasonally thawed layer has increased from 1.2 m (2000) to 1.8 m (2016), which exceeds the depth of potential freezing for this area; thus, subsidence of the permafrost table has already begun. In the Kumzha area, with a thickness of the active layer of 2 to 2.5 m, the permafrost table in the central part of the grid lowered from 2.6 m (2015) to 3.0 m (2016), and in the marginal part with shrubs up to 1.5 m high – from 6.2 to 7.1 m, respectively.

In the southern tundra zone in the Vorkuta region, taking into account thaw subsidence, the permafrost table lowered by 0.6 m from 1999 to 2015 [*Kaverin et al., 2017*].

The greatest lowering of the permafrost table has been recorded in the forest-tundra zone in well-drained areas with high shrubs favorable for snow accumulation. In the area of borehole 5-01, the lowering of the permafrost table began in the early 1990s, accelerated in the 2000s, and reached a depth of 10 m by 2014. After 2014, the position of the permafrost table has fluctuated around a depth of approximately 10 m. At borehole 5-08, the permafrost table lowered by approximately 7 m by 2010. At the end of 2010, this borehole collapsed, and observations were terminated.

In the northern taiga zone, only bogs, linear ridges, and peat mounds are frozen. Lowering of the permafrost table in the Nadym region was observed only in bogs and by 2018 it reached about 4 m. Frozen palsas and lithalsas remain relatively stable, and no permafrost degradation has been observed here. In the Tarko-Sale monitoring station, palsas and linear peat ridges are still frozen. The permafrost table in palsas remains stable, while within ridges composed of mineral soils it has dropped to a depth of 6 m.

To determine properly the stages and mechanisms of permafrost degradation, it is very important to take into account the structure of the upper soil horizons. In the structure of the upper permafrost, the following layers are distinguished from top to bottom [*Shur, 1988*]: a) active layer, b) transient layer, c) intermediate layer, and d) original permafrost. A transient layer is a soil layer that belongs to the permafrost for several years and may thaw only under favorable climatic conditions [*Shur, 1988*]. Its thickness is small and reaches up to 10–15 % of the average thickness of the active layer in mineral soils and up to 40 % in peat. Such a layer was distinguished in 1933 by Yanovskiy, who noted its high silt content and a slight increase in moisture content in comparison with the active layer. At present time, when significant climate warming has led to increase in the active layer thickness, we can assume that the entire former transient layer has already joined the active layer, i.e. it thaws and freezes annually.

The intermediate layer is a typical horizon in the upper part of the permafrost, which was identified and described in detail by Shur in the mid-1980s [*Shur, 1988*]. One of his hypotheses of formation of this layer is the re-freezing of a part of the permafrost that had thawed from the surface during the period of the climatic optimum. A characteristic feature of the intermediate layer is its extremely high ice content. The thickness of the intermediate layer can reach 2–3 m. The intermediate layer plays a protective role during climate warming that leads to increase in the depth of seasonal thawing. Thawing of the intermediate layer requires significantly greater heat input due to its high ice content and therefore its occurrence prevents thawing of the underlying permafrost. With a long-term increase in mean annual and summer air temperatures, the intermediate layer may completely thaw, and in this case accelerated degradation of underlying permafrost will begin.

A combined analysis of the data on mean annual ground temperature at the base of the active layer and in the permafrost at different depths (up to the depth of zero annual amplitudes), and the rate of lowering of the permafrost table allowed us to develop a conceptual model and distinguish three stages of permafrost degradation during climate warming (Fig. 7).

At the first stage, the depth of seasonal thawing increases, and in some especially warm years the transient layer becomes a part of the active layer. Mean annual ground temperature is still negative, and at this stage permafrost can be considered stable.

At the second stage, with the further warming of the climate, mean annual ground temperature of the active layer becomes positive, thawing of the intermediate layer begins, and after its complete thawing it loses its protective function. Soils of the active layer transform from seasonally thawed to seasonally frozen state. This stage can be considered transitional, and state of permafrost can be considered unstable.

Finally, at the third stage, the thawing of permafrost from above continues along with relatively fast lowering of the permafrost table and formation of closed talik. Positive mean annual ground temperature is observed not only in the active layer, but also in the developing closed talik. This stage is characterized by progressive permafrost degradation.

An analysis of the spatial distribution of permafrost degradation in the western sector of the Russian Arctic reveals that in the typical tundra zone mean annual ground temperatures of the permafrost and active layer remain negative, and permafrost is in a stable state.

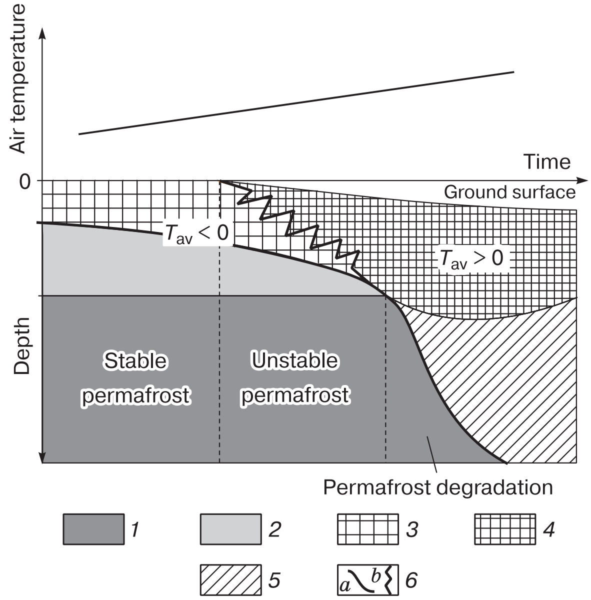

Fig. 7. Stages of permafrost reaction to climate warming:

1 – permafrost; *2* – intermediate layer; *3* – seasonally thawed layer; *4* – seasonally frozen layer; *5* – unfrozen soils area; *6* – position of the permafrost table over time (*a*) and the conditional boundaries of the transition from seasonal thawing to seasonal freezing (*b*). Line it is a linear trend in air temperature; T_{av} it is the average annual ground temperature.

In the southern tundra, mean annual ground temperature of the permafrost remains negative, but mean annual ground temperature of the active layer has become positive. Thawing of the intermediate layer has begun. Permafrost is in transitional, unstable state. In this bioclimatic zone in landscapes with high shrubs, progressive permafrost degradation may begin in the coming years.

In the zones of forest-tundra and northern taiga, mean annual ground temperature of the active layer is positive, and mean annual ground temperature of the underlying permafrost is approaching 0 °C, and progressive permafrost degradation and rapid lowering of the permafrost table have been observed.

It should be mentioned that these observations can be applied only to landscapes with the greatest vulnerability to climate change. In landscapes with high resistance to climate warming, permafrost can remain in a stable or transitional state even within southern bioclimatic zones.

Observations showed that climate warming leads to increase in mean annual ground temperature of the active layer up to positive values and increase in depth of seasonal thawing, and subsequently more favorable conditions develop for growth of vegetation cover and shift of the boundaries of bioclimatic zones to the north (Fig. 8).

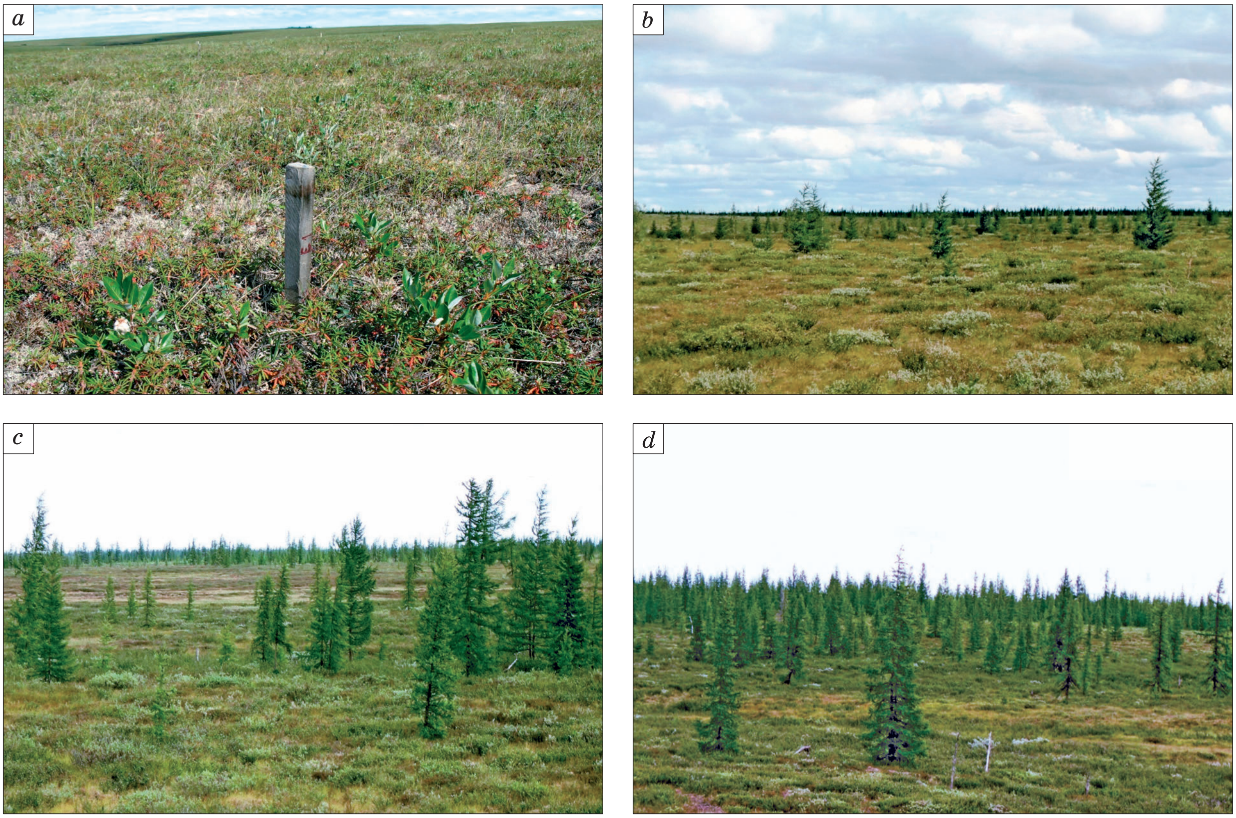

Fig. 8. Changes in vegetation in the Yuzhniy (South) Urengoy study area during climate warming.
a – 1970s; *b* – 1990s; *c* – 2000s; *d* – 2010s. Photo by D.S. Drozdov.

Migration of the tree line to the north that occurred in the area of Yuzhniy (South) Urengoy from 1975 to 2018 is estimated to reach approximately 30–40 km. Moreover, climate warming leads not only to growth of forest vegetation, but also to increase in the projective cover of shrubs and, in general, to decrease in diversity of landscape mosaic.

CONCLUSIONS

Analysis of the results of long-term monitoring of permafrost conditions at stations in the western sector of the Russian Arctic allows us to make the following conclusions:

From 1970 to 2018, mean annual air temperature in the region increased by approximately 2.8 °C, which is close to the worst-case scenario of climate change. Climate warming is accompanied by 5–10 % increase in annual precipitation and increase in snow cover thickness in the tundra zone at a rate of 1.8 cm/year (1998–2018), and in the forest tundra and northern taiga zone at a rate of 0.6 cm/year (2003–2018).

In all bioclimatic zones and in all dominant landscapes an increase in mean annual ground temperature of permafrost has been observed along with warming climate. The greatest changes in mean annual ground temperature have been observed in the typical tundra zone. The average temperature increase here has reached 0.056 °C/year. In the southern tundra and forest-tundra zones, the rate of increase in mean annual ground temperature of permafrost has varied from 0.04 to 0.05 °C/year, and in the zone of the northern taiga it has reached 0.035 °C/year.

Since 2007, in all bioclimatic zones, except for the typical tundra, mean annual ground temperature of the active layer has reached positive values, and thawing of permafrost from above has begun (i.e., permafrost degradation). At the same time, degradation processes have not developed in all landscapes, but only within landscapes that are most sensitive to climatic changes.

Thawing of permafrost from above is accompanied by lowering of the permafrost table. In the forest-tundra zone, it already started in the mid-1990s and in well-drained areas it has reached a depth of 7 to 10 m. In the southern tundra zone, the maximum lowering of the permafrost table has reached 7 m in well-drained ice-poor sandy soils with a well-developed shrub vegetation. In other cases, lowering of the permafrost table has not exceeded 2 m. In the northern taiga zone, permafrost table has lowered by 4 to 6 m.

We propose to distinguish three stages of permafrost degradation caused by climate warming. At the first stage, the depth of seasonal thawing increases, and mean annual ground temperature rises. At this stage, mean annual ground temperature is still negative, and permafrost can be considered stable. At the second stage, the depth of seasonal thawing exceeds the thickness of the transient layer and affects the intermediate layer. Values of mean annual ground temperature in the upper horizons become positive. Thawing of the intermediate layer and lowering of the permafrost table begins. This stage is characterized by unstable state of permafrost. If mean annual ground temperature in the upper horizons becomes positive, and a thickness of the thawed layer becomes greater than a combined thickness of the active and intermediate layers, the stage of active permafrost degradation, which is accompanied by fast lowering of the permafrost table, begins.

Permafrost degradation, along with climate warming, is favorable for the active growth of vegetation and a shift of boundaries of bioclimatic zones to the north.

Monitoring of the thermal regime of permafrost has been performed within the framework of the state task, according to the Research Plan of the Tyumen Scientific Center of the SB RAS for 2018–2020, protocol No. 2 of 08.12.2017. Analysis and interpretation of conditions and rates of permafrost degradation have been performed with the support of the Russian Foundation for Basic Research (RFBR) grant 18-05-60004; studies of the impact of climate change on vegetation have been supported by the RFBR grant 18-55-11005. Field work at monitoring sites in the European North and West Siberia in 2016–2019 were performed with the financial support of the grant of the Russian Science Foundation 16-17-00102.

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