Monitoring of cryogenic geosystems in the European North, their current condition and dynamics

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ABSTRACT
This paper provides results of monitoring of cryogenic (permafrost-affected) geosystems at the permafrost monitoring stations Bolvansky, Kashin, and Shapkina, in region of the European North of Russia. The interannual dynamics of permafrost temperatures, and of the seasonal thawing depth have been studied. The trends in increase of ground temperature (T_{ground}) in various cryogenic geosystems lag behind trends in air temperature (T_{air}). The Tair trend for the 30-year period shows an increase of 0.07ºC/year, while for T_{ground} it varies from 0.01 to 0.03ºC /year. In the last two years, the active layer thickness has reached its maximum value, and the closed taliks began to form at the hilltops underlain by ice-poor permafrost.

RÉSUMÉ
Cet article présente les résultats de la surveillance des géosystèmes cryogéniques aux stations géocryologiques Bolvansky, Kashin et Shapkina situées dans la zone de pergélisol dans l'Europe du Nord. Dans le contexte de réchauffement climatique d'aujourd'hui, les tendances des températures du pergélisol à augmenter et la dynamique interannuelle de la profondeur de gel saisonnier ont été étudiées. Il est montré que les tendances caractérisant les variations de température des divers géosystèmes cryogéniques présentent un retard par rapport aux tendances affectant la température de l'air. En considérant une période de 30 ans, la tendance associée à la T_{air} est de 0.07°C/an et celle associée à la $T_{pergélisol}$ est de -0.01 à 0.03°C/an. Au cours des deux dernières années, la profondeur de dégel saisonnier a atteint sa valeur maximale, pour l'ensemble de la période d'observation, où l'inertie thermique du pergélisol est faible. Les taliks ont donc commencé à se former sur les sommets des collines où les dépôts présentent une faible teneur en glace.

1 INTRODUCTION

Monitoring of cryogenic geosystems in the permafrost region (permafrost monitoring) is a unified observation system, which includes assessment, monitoring, and forecast of the environmental changes triggered by climatic and anthropogenic factors in areas with permafrost or seasonal freezing. During permafrost monitoring in various geosystems, special attention should be paid to the influence of climate change and human activities on the thermal regime of permafrost and dynamics of permafrost-related processes (Pavlov, 2008).

By the end of the 1980s, the total number of different objects for regular observations (including areas, monitoring stations, study sites, and transects) in the European North of Russia reached 110, and the number of observation points (grids, boreholes, and fixed points) exceeded 600, including those in the Nenets Autonomous Region (10 stations and more than 100 observation grids and boreholes). In mid-1990s, due to economic problems in Russia, most of the monitoring objects were closed or turned in stand-by status.

During the last 20 years, the development of oil and gas fields in the European North has been progressing rapidly. The building of the oil terminals in the coastal zone of the Barents Sea and Pechora Bay (Varandey and others) is in progress. However, the current data on the changes in permafrost conditions have turned out to be insufficient for engineering needs.

In the Nenets Autonomous Region, there are currently only two active monitoring stations – Bolvansky and Kashin. In 2014, we examined the abandoned Shapkina station and prepared several boreholes for the continuation of temperature measurements (fig.1).

In this paper, the changes in permafrost that have occurred in the cryogenic geosystems during the last 30 years and their relation to observed climatic changes are analyzed.

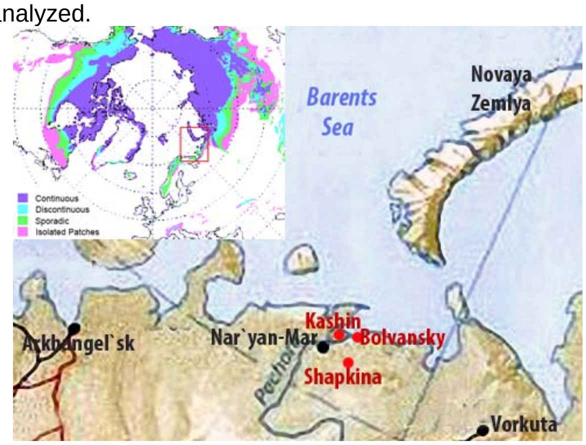

Figure 1. Key monitoring sites

2 METHODS

Field study of permafrost conditions included landscape description of transects and control points, drilling of boreholes and testing of soils, and application of geophysical methods for determination of permafrost table position, permafrost thickness, and boundaries of taliks.

Measurements of the active layer thickness using the permafrost probe were carried out at the monitoring grids located within the dominant landscapes in accordance with the CALM program [Brown et al., 2000]. The measurements of air, ground surface, and permafrost temperatures in the boreholes (at depths of 1, 3, 5, 7 and 10 m) were conducted in accordance with the procedures of the Thermal State of Permafrost (TSP) project (Romanovsky et al., 2010).

The automated sets HOBO U12 data loggers were installed at monitoring grids and boreholes located in various landscapes. The temperatures have been recorded 4 times per day year-round. The obtained information was processed in accordance with the prescribed TSP protocol. Daily, monthly, and annual ground temperatures means were calculated. Charts, trend lines, and regression equations were made using the Microsoft Excel program.

3 LOCATION OF MONITORING STATIONS AND GENERAL CHARACTERISTICS OF THE STUDY AREAS

The long-term permafrost monitoring station Bolvansky, R24 (68º17.3`N, 54º30.0`E) is located next to the Pechora River Delta, on the northernmost edge of the Bolvansky Cape, on the shore of the Pechora Bay of the Barents Sea. The area belongs to the undulating IV Marine Plain covered by southern tundra with numerous lake depressions and large flat-bottom valleys, some of them with permanent creeks. Elevations range from 25 to 35 m a.s.l. Soil is near shore Quaternary deposit, presented by sandy loam with boulders to a depth more than 100 m. Polygonal peatlands and fens with peat thickness ranging from 0.5 to 5 m occupy the inter-hill areas and depressions. The Bolvansky station is located at the southern border of the continuous permafrost zone. The thickness of permafrost in this area varies from 100 to 200 m [Oberman and Mazhitova, 2001].

At elevated and flat sites, permafrost occurs just below the active layer whereas a lowered permafrost table is typical of valley bottoms, both dry and with flowing water. Open taliks occur under the Pechora River valley, under the Pechorskaya and Bolvanskaya Bays, and under many deep lakes (Mazhitova et al., 2004, 2008).

Using seismic methods, it was found that the permafrost table was lowered from 3 m in the upper part of the slopes to 8 m in the bottom of lake depressions. Seismic studies carried out in gullies and small valleys detected the development of shallow taliks up to 5.5 m deep [Melnikov et al., 2010].

Initial permafrost studies at the monitoring station Bolvansky were carried out from 1983 to 1993 by researchers from the Timanskaya Geological Survey Office and VSEGINGEO. After 1999, the observations were continued by the Earth Cryosphere Institute (ECI SB RAS) in all temperature boreholes and at the CALM site established for the study of the active layer dynamics [Malkova, 2010].

In 2009, the new permafrost monitoring station R24-A Kashin Island, was established (68º14.5'N, 53º51'E). It is located on I Marine Terrace (10 m a.s.l.) approximately 50 km to the west of the station R24 Bolvansky. Kashin Island is a small island in the Korovinskaya Bay in the outer part of the Pechora River Delta. Although both sites (R24 and R24-A) are located in the continuous permafrost zone, in some areas local conditions may be favorable for formation of taliks. Kashin Island is composed mainly of frozen sand; peat layers of various thickness can be found locally in the upper permafrost. According to geophysical data, the permafrost thickness on the island reaches 30 to 40 m [Sadurtdinov et al., 2012].

The permafrost monitoring station Shapkina (67º34'N, 55º07'E) is located 100 km to the south of the coast of the Pechora Bay, within V Glacial-Marine Plain with an altitude of about 100 m. Regular permafrost studies were conducted at this site in the period from 1983 to 1993 by the Timanskaya Geological Survey Office, after that the study site was abandoned for more than 20 years. In the summer of 2014, we examined a part of the boreholes at this site and performed measurements of ground temperature.

The surface topography is characterized by gentle hills dissected by stream valleys and ravines. Surficial middle Quaternary sediments are represented by marine and glacial-marine silty clays with layers and lenses of sands. On flat areas and in the saddles of the hills the surface is underlain by peat up to 3 m thick. Surficial soils are predominantly frozen [Oberman, 2007]. Lowered permafrost table was observed mainly in valleys and gullies with thick willows, or at the foot of the slopes where large amounts of snow accumulate.

4 RESULTS AND DISCUSSION

As a result of 30 years of observations at the **Bolvansky station**, unique actual data was obtained, allowing to study both cyclic and trend changes in the active layer thickness and temperature of frozen soils.

The mean annual permafrost temperature at 10 m depth depends on landscape conditions and varies from –0.5°C to –2.5°C (according to measurements in 25 boreholes).

In the elevated areas and on tops of the hills the permafrost temperature varies between –2.0°C and –2.5°C. Within polygonal peatlands, on the slopes, and in the saddles of hills with tundra vegetation, the permafrost temperature varies from –1.5°C to –2.0°C. At the lakeshores and edges of terraces, and the headstreams of small creeks, typical permafrost temperatures are in the range of –0.6°C to –1.4°C.

At the bottoms of ravines and under lakes, permafrost table is lowered from several meters to dozens of meters, and temperature of unfrozen ground at the depth of 10 m varies from +0.3°C to +1.0°C [Malkova, 2010].

Since 1983, the mean annual air temperature (MAAT) at the weather station Bolvansky increased by 3 °C, while the mean annual permafrost temperature (MAPT) in various landscapes increase only by 0.2 to 1.0°C. An increase in MAAT is 0.07°C/year, while an increase in MAPT is significantly lower – from 0.01 to 0.03°C/year (fig. 2).

The steepest trend of the MAPT is characteristic of the low temperature permafrost landscapes, and the lowest trend – of the high temperature landscapes [Malkova, 2010, 2011; Drozdov et al., 2012].

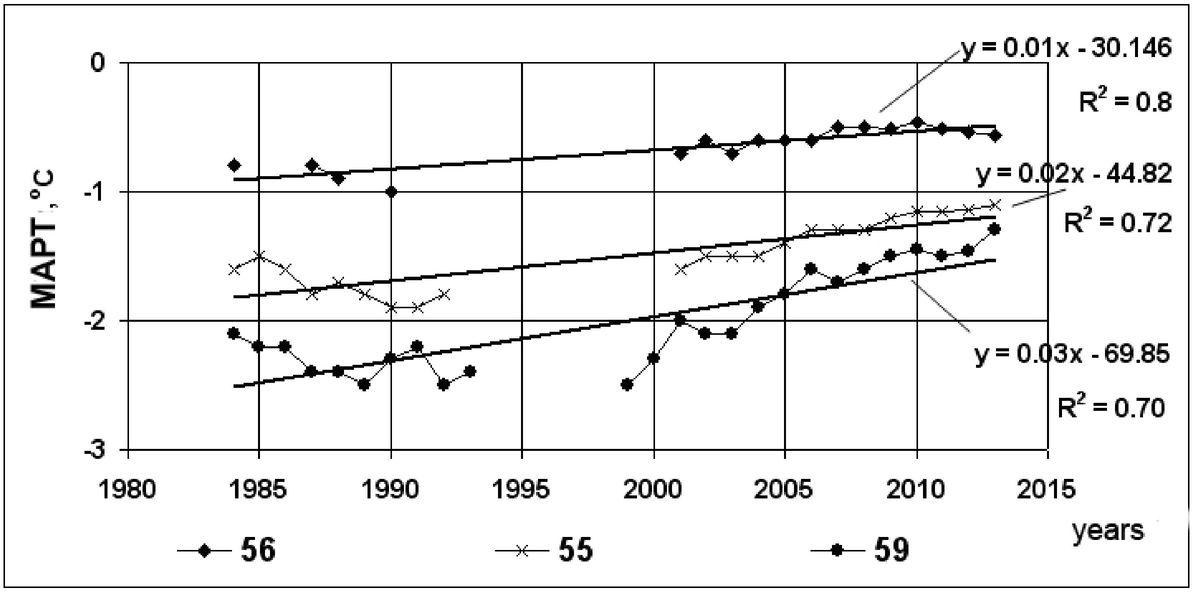

Figure 2. Mean annual permafrost temperature (MAPT) at the depth of 10 to12 m, Bolvansky station. Borehole 59 – the top of the hill, drained tundra; borehole 55 – polygonal peatland; borehole 56 - the edge of the terrace, slope, tundra.

After a few unusually warm years, average annual temperature at the base of the active layer increased from –2...–3°C in the 1980s to 0...–0.2°C in 2011 and 2012 (fig. 3A). As a result, the permafrost table is lowered in local areas within the CALM site R24. Such areas include tundra landscapes on the hilltops, formed by ice-poor loam with MAPT of –1 to –2°C. Sites with peat on the surface remain stable even at a temperature of 0 to –1°C (fig. 3B).

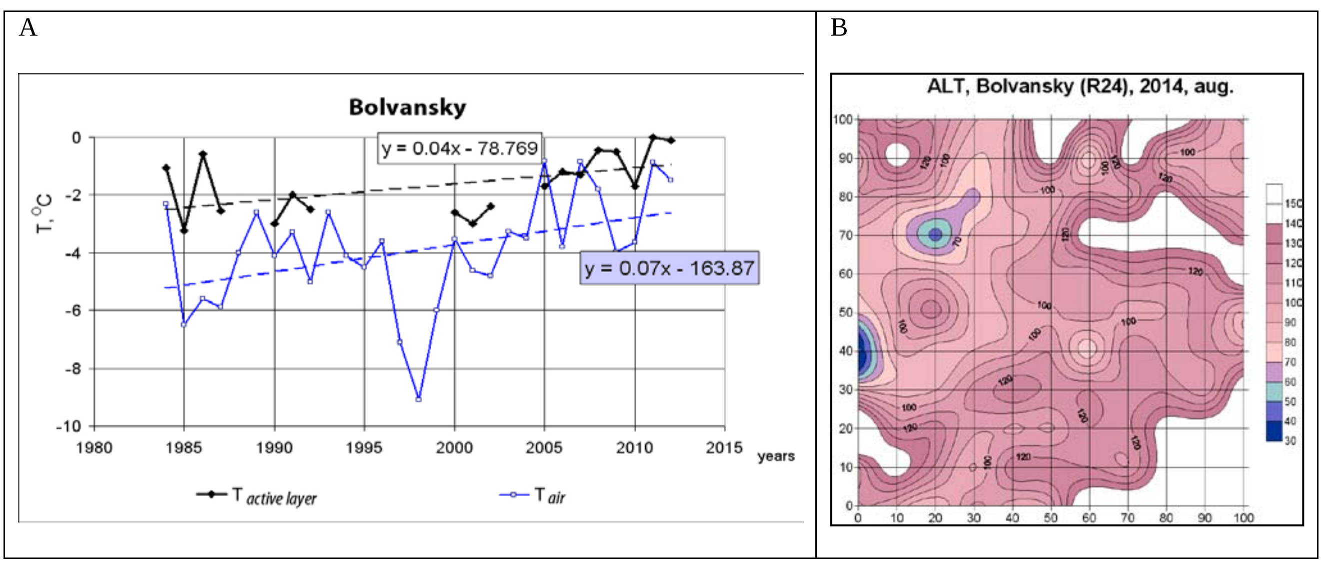

Figure 3. Temperature dynamics and the active layer thickness at the Bolvansky station: A - the mean annual air temperature (MAAT, blue line) and mean annual active layer temperature (MAALT, black line); B - map of the active layer thickness (ALT) at the CALM grid 100x100 m in 2014.

In 2012, two parametric boreholes were drilled at the **Kashin station**: borehole 1, located at the elevated area with drained tundra, elevation 10 m a.s.l.; and borehole 2, located in the peat bog near the shore of the island, near the shallow ravine, elevation 2 m a.s.l. In these boreholes, permafrost temperatures have been measured at depths 1, 2, 3, 4, 5, 6, 8, and 10 m from the surface. In 2012, MAPT in borehole 1 at 10 m was –1.9°C, while in borehole 2 it was only –0.9°C. During the three years of measurements in borehole 2 at a depth of 10 m, permafrost temperature has gradually increased by 0.3°C and reached –0.6°C in 2014, while in borehole 1 it has increased by 0.5°C and reached –1.4°C. This very significant and rapid change in thermal state of permafrost was obviously triggered by climate anomalies of the recent years. Continued observations will allow to assess the dynamics of permafrost with further climate change in these landscape conditions.

Preliminary results of the studies of the permafrost temperature dynamics were obtained in the boreholes at the **Shapkina station**. In the summer of 2014, we reexamined this site and measured ground temperature in several boreholes. For the 30-year period, permafrost temperature at depths of 10 to 12 m has increased significantly. The greatest changes have occurred in the hilltop geosystems with flat poorly drained shrub-moss tundra (borehole 12). In 1983, permafrost temperature there was –1.7°C, and in 2014 it was only –0.6°C, i.e. there was an increase of 1.1 °C. In wetland geosystems with fens and marshes (borehole 8) the changes in temperature were the lowest. In 1983, permafrost temperature at a depth of 10 m was –0.7°C, and in 2014 it was –0.4°C. An intermediate changes in MAPT were detected within the flat peatlands (borehole 9) (fig. 4).

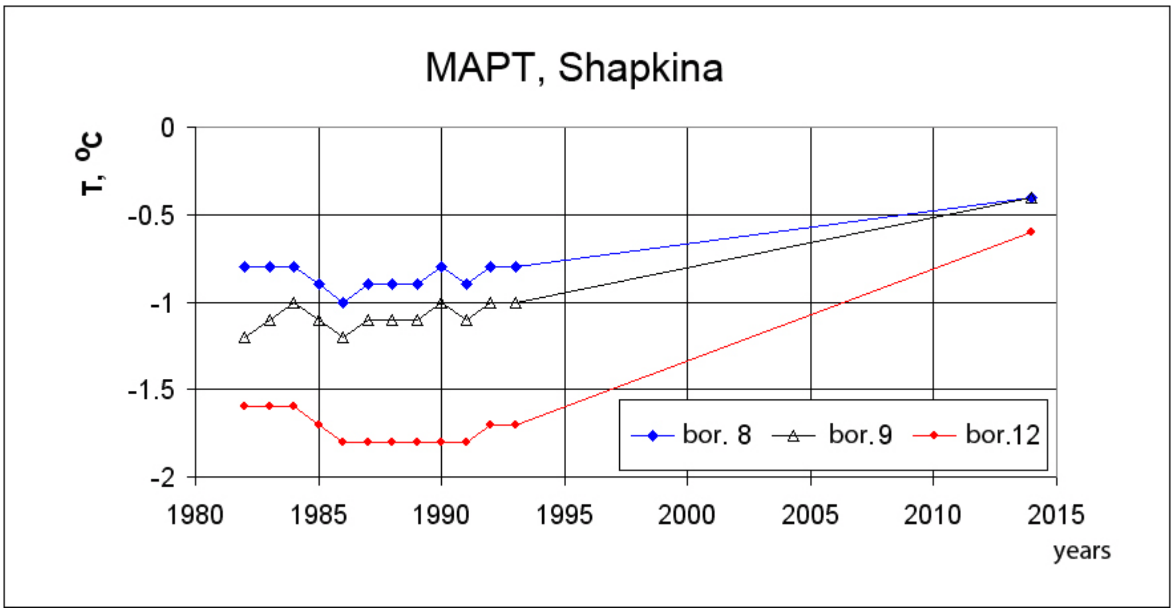

Figure 4. Mean annual permafrost temperature (MAPT) at the depth of 10 m in boreholes 8 (bog), 9 (peatland), and 12 (flat tundra), Shapkina station

In 1980s, temperature monitoring boreholes were established in disturbed areas with locally removed vegetation around the Shapkina station. During inspection of this site in 2014, it appeared that all boreholes in the disturbed area were filled with ice and unsuitable for the continuation of temperature measurements. It was found out that due to the change of heat exchange on the ground surface the permafrost table within the disturbed areas lowered by 4 to 5 m.

The active layer thickness (ALT) measurements are an important part of the permafrost monitoring. After 14 years of regular observations, ALT within the CALM site R24 at the Bolvansky station has increased by 20 cm, so the ALT increase trend reaches 1.5 cm/year, while this trend in 1983-1993 was only 0.1 cm/year [Malkova, 2011; Drozdov et al, 2012].

Significant increase in ALT was recorded in 2012. In the winter of 2012/2013, the lower part of the active layer remained unfrozen due to warm winter with thick snow cover.

ALT dynamics at the Kashin Island station have been studied during the 5-year observations at the CALM site R24-A. Within the grid area, almost everywhere there is a surficial peat layer from 5 to more than 25 cm thick, which provides a good insulation and preserves permafrost. ALT there highly correlates with conditions of the surface and the thickness of peat.

ALT in the different conditions increases in the following order: peat mounds, peatlands, bogs, hillock moss-lichen tundra, grass-lichen tundra, and lichen tundra.

The minimum depth of seasonal thawing of 40-50 cm is observed at sites with a thickness of peat of 20 cm or more, while the greatest ALT of up to 110 cm was detected in drained tundra with a peat thickness of less than 5 cm (fig.5).

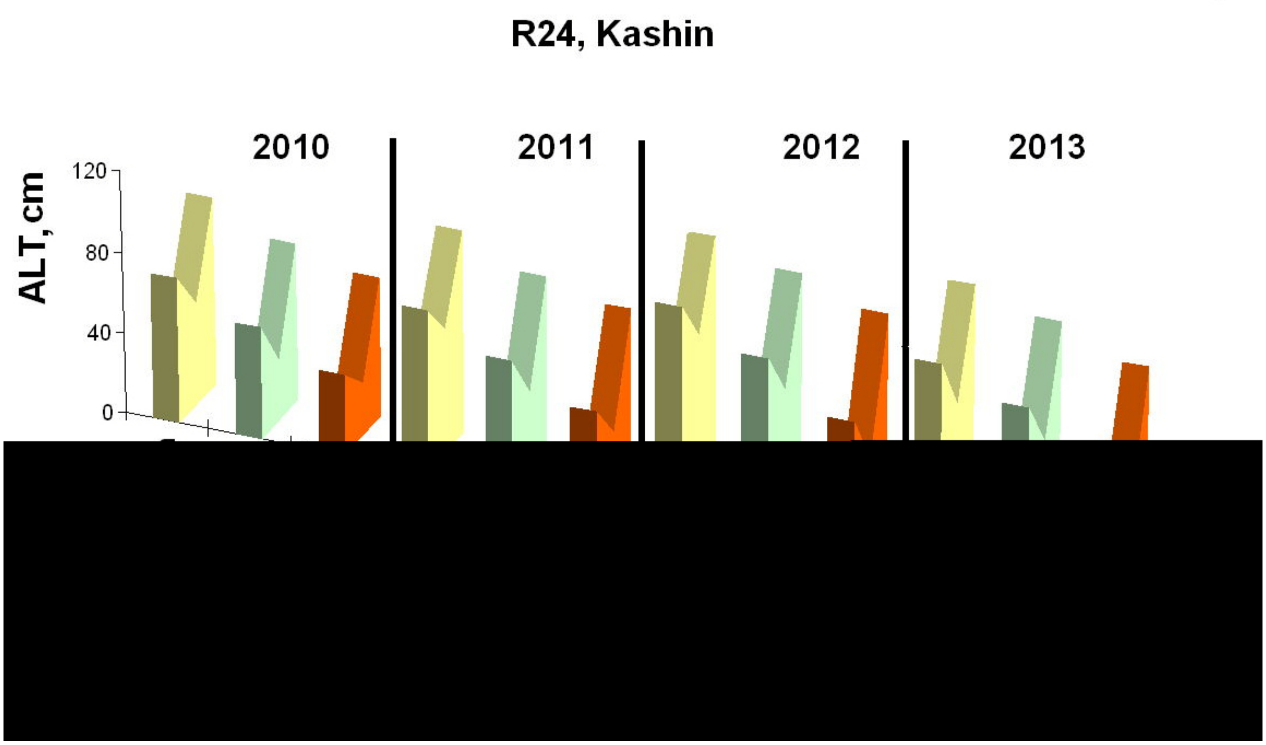

Figure 5. The active layer thickness (ALT) dynamics and the peat thickness, Kashin station

During the five years of studies at the Kashin station, ALT has increased by 15 to 20 cm. The average depth of thawing was 58 cm in 2010, 64 cm in 2011, and 88 cm in 2012 and 2013, which means a 50% increase.

This is explained by the significant increase in air temperature in summer and earlier snow melting during the last 3 years. Despite a dramatic increase in ALT, no closed taliks have been formed on Kashin Island, unlike the Bolvansky station area. In 2014, ALT significantly decreased everywhere within the R24-A grid as a result of relatively cool summer.

No studies of the ALT dynamics have been performed at the Shapkina station.

5 CONCLUSIONS

Permafrost is a major environmental factor of the Arctic terrains. Long-term permafrost monitoring is essential to assess the current state and tendencies of changes in cryogenic geosystems in the conditions of global warming and significant climate variations. In the European North of Russia, the period from 1983 to 2014 is characterized by a significant increase in MAAT, equal to 0.07 ºC/year.

The thermal state of permafrost have some inertia, and an increase in MAPT under the natural conditions have been 2 to 7 times smaller than an increase in MAAT. The temperature of the active layer reacts to changes in the air temperature much faster than underlying permafrost. In dominant landscapes, the mean annual active layer temperature has increased from –3.5 ºC in 1980s to 0 ºC in 2011-2012, which caused the lowering of the permafrost table and formation of closed taliks between the active layer and permafrost.

To assess the impact of combined effects of climatic and anthropogenic changes in cryogenic landscapes, it is necessary to expand the monitoring network, use automated data collection, and widely apply remote sensing and geophysical methods to determine the of permafrost characteristics.

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