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SOIL TEMPERATURE IN THE CONTEMPORARY NATURAL-CLIMATIC SITUATION OF THE STEPPE BAIKAL REGION (ON THE EXAMPLE OF OLKHON ISLAND)

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The paper analyzes the current temperature state of frozen and thaw soils in the Baikal region (Olkhon Island). It is shown that the current trend in soil temperature is directly related to climate change in and to the increase in the atmospheric air temperature. Permafrost within Olkhon Island is significantly transformed: the processes in soils are aimed at the degradation of frozen formations.

Keywords: *permafrost, temperature regime, seasonally thawed and seasonally frozen layer.*

INTRODUCTION

The purpose of this work is to estimate the state of the seasonally thawed and seasonally frozen layers near the southern boundary of the cryolithozone under conditions of recent climate change. The basic task of the study is to determine the temperature regime of permafrost and unfrozen soils and its transformation under conditions of freezing and thawing.

Climate significantly affects the thermodynamic regime of permafrost: changes in the air temperature can activate geocryological processes [*Grosse et al., 2011; Malkova et al., 2011*]. A positive trend in the air temperature has been established for the entire Baikal region: in 1965–2003, the temperature increased by 0.042–0.046 °C/yr [*Pavlov, 2008; Malkova et al., 2011*]. Within the steppe zone in the Baikal region, on the Olkhon Island, an increase in the air temperature has led to the establishment of positive (above 0 °C) mean annual air temperatures in the recent years. Over the past 65 years, the trend of the mean annual air temperature has been 0.03 °C/yr (Fig. 1) [*http://gis.ncdc.noaa.gov; http://www.pogodaiklimat.ru*]. We have also calculated mean seasonal air temperatures for the cold and warm seasons corresponding to a hydrological year.

The main changes in the thermodynamic regime of permafrost depend on the air temperature. This is primarily reflected in the state of the seasonally frozen or seasonally thawed layers, where the main heat exchange occurs in the annual cycle of heat turnover [*Kudryavtsev, 1978*]. Changes in the thermal state of permafrost and permafrost degradation may continue for decades and centuries [*Balobaev, 1971*]. Therefore, the short-term studies do not always identify degradation of permafrost, whereas temperature changes in the active layer allow us to judge the re-

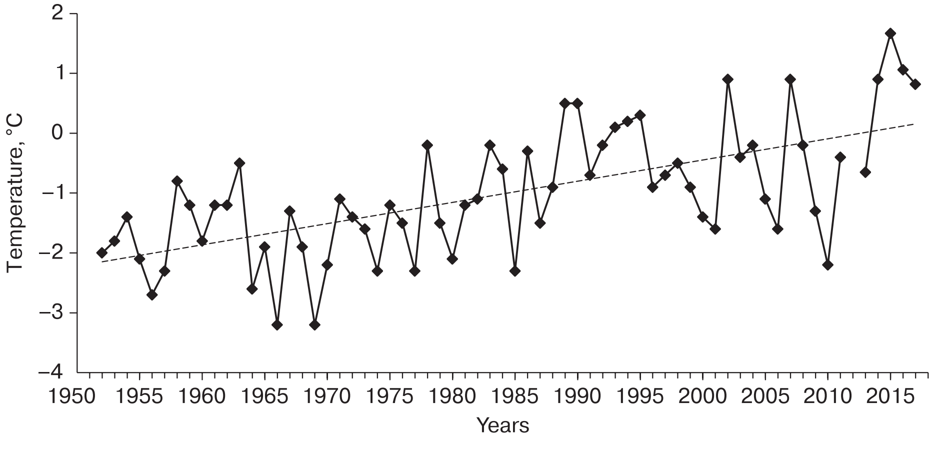

Fig. 1. Atmospheric air temperature on Olkhon Island; data from the Uzura weather station, 462 m a.s.l.).

sponse of permafrost to the contemporary climate transformation and the direction of these processes.

STUDY AREA

Olkhon Island is located in the central part of Lake Baikal, on the border of the North Baikal and Middle Baikal depressions (Fig. 2) [*Lut, 1978*]. Detailed studies of the temperature regime of soils have been conducted on the western coast of Olkhon Island, northeast of the Kharantsy settlement, between Kharantsy and Kharaldai capes. The study site is allocated to a gentle slope of northwestern aspect; the slope surface topography is complicated by landslides of varying degrees of activity.

The entire Baikal steppe region is deficient in atmospheric precipitation. On Olkhon Island, annual precipitation ranges from 197 to 278 mm, and the annual ratio of precipitation to potential evapotranspiration is 0.34. Precipitation in the winter is particularly small; the snow cover depth does not exceed 10–15 cm [*Imetkhenov et al., 1997; Pellinen, 2018*]. The vegetation cover is poor and is represented mainly by steppe and meadow herbs [*Khimenkov et al., 2015*]. In the areas with permafrost, the vegetation cover is denser and richer. Surface sediments are mainly represented by the Quaternary colluvium (deluvial-proluvial sediments) and Neogene lacustrine and lacustrine-bog sediments. These sediments are involved in various exogenous geological processes [*Palshin, 1968*]. In terms of geocryology, this area belongs to the zone of isolated patches of permafrost. According to F.N. Leshchikov [*1978*], the thickness of permafrost in this zone does not exceed 10–15 m, the mean annual permafrost temperature ranges from –0.1 to –0.2 °C, and the permafrost table lies at a depth of 2.0–2.5 m. The mean annual temperature of the active layer above the permafrost table is from –0.1 to –0.5 °C. The depth of seasonal freezing-thawing does not exceed 2.0–2.5 m. According to the thermal regime, permafrost in such areas is extremely unstable and may be subjected to degradation in the case of disturbances of the natural environment.

Four boreholes were drilled within the study area: Olh-12-1 with a depth of 3.5 m, Olh-13-1 with a depth of 8.0 m, Olh-13-2 with a depth of 9.0 m, and Olh-13-3 with a depth of 15.0 m. These boreholes can be divided into two groups: with and without permafrost (Fig. 2). Boreholes of the first group (Olh-12-1 and Olh-13-1) were drilled in the area of permafrost. The lithological section was studied to a depth of 8.0 m. The upper part of the section consisted of lacustrine clayey sediments with thin (1–3 cm) interlayers of loamy sand from a depth of 1.0 m. Temporary perched water was found at a depth of 1.5 m. Its presence resulted in an increased water content (up to 30 %) in the upper part of the section (0.5–1.0 m). From a depth of 1.9 m, the sediment was in the frozen state.

Boreholes of the second group (Olh-13-2 and Olh-13-3) were found 300 m away from the first group and penetrated unfrozen ground. Its lithological section of was studied to a depth of 15.0 m and consisted of clayey sediments with interlayers of sand. The lower part of the section was composed of clay of the lacustrine origin. The groundwater table was at a depth of 4.5 m. The water content in the upper part of the section (0.5–1.0 m) did not exceed 4–5 %. To determine the air temperature, a temperature sensor was installed at a height of 2.5 m at about 800 m southwest of the boreholes of the first group.

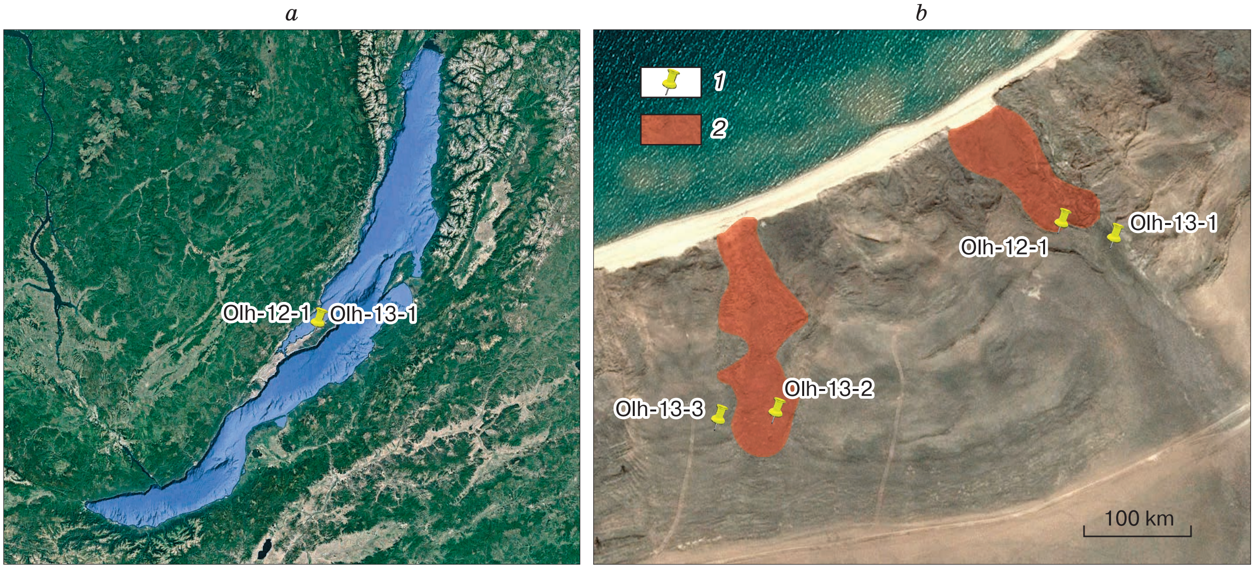

Fig. 2. Study area (*a*) and location of monitoring boreholes (*b*).

1 – boreholes; *2* – areas affected by landslides.

METHODS

Geocryological monitoring was carried out in the observation boreholes Olh-12-1, Olh-13-1, Olh-13-2, and Olh-13-3 in agreement with the recommendations of the Global Terrestrial Network for Permafrost (GTN-P) program, which is part of the Global Climate Observing System of the World Meteorological Organization. At the initial stage, the observation network was arranged on the basis of available technical means in order to determine the dynamics of changes in the temperature regime of soils within the seasonally thawed and seasonally frozen layers. The temperature sensors in borehole Olh-12-1, which was drilled in August 2012, were installed at the depths of 0.6 m, 1.0 m, 1.6 m and 3.5 m. In August 2013, boreholes Olh-13-1, Olh-13-2, and Olh-13-3 were drilled, and the temperature sensors were installed in them at the depths of 0.1 m, 2.0 m and 4.0 m. The maximum depth of the installation of the temperature sensor in borehole Olh-13-3 was 9.3 m.

We used temperature sensors (loggers) produced by the Onset Computer Corporation: HOBO U12-008, HOBO Pro V2 Temperature/Relative Humidity Data Logger, and HOBO UA-001-64 Pendant Temperature/Alarm (Waterproof) Data Logger. Loggers of the HOBO U12-008 type were installed in boreholes Olh-12-1, Olh-13-2, and Olh-13-3; they ensured the accuracy of measurements of ±0.1 °C. Loggers of the HOBO Pro V2 type with the accuracy of measurements of ±0.2 °C were installed in borehole Olh-13-1. Logger HOBO UA-001-64 recorded the air temperature with an accuracy of ±0.4 °C. The air and soil temperatures were recorded every hour.

RESULTS

Air temperature. According to the results of air temperature measurements performed since 2013, the mean annual air temperature in the study area ranges from –1.2 to 1.7 °C, which is close to the results obtained at the Uzury weather station (462 m a.s.l.) located in the steppe zone to the north of the study area.

The calculation of the mean annual temperatures corresponds to the hydrological year and includes two periods: winter (October to March) and summer (April to September). During the observation period from 2013 to 2018, the mean annual air temperature in the study area rose above 0 °C. An insignificant, but stable increase in the air temperature took place in the warm (summer) period (April–September) (Fig. 3, *a*). In 2013, the mean air temperature during the warm period was 9.6 °C; in 2018, it reached 12.1 °C. In the cold (winter) period (October–March), the general trend of the air temperature also demonstrates a positive trend, although a longer observation period is required for reliable conclusions (Fig. 3, *b*). A significant rise in the temperature of the cold season (by 4.8 °C) took place in 2014 in comparison with 2013. However, since 2014, the mean values of the air temperature during the cold season have decreased from –7.4 to –10.3 °C.

Soil temperature. In 2012, in borehole Olh-12-1, permafrost at a depth of 3.5 m was characterized by the subzero mean annual temperature of –0.1 °C [*Svetlakov, 2018*]. Since the beginning of our observations, the temperature at the top of permafrost remained in the subzero range throughout the year up to 2015. In 2015, the transition from to above-zero temperatures at this depth took place in the annual cycle, i.e., the permafrost table lowered, and the thickness of the seasonally thawed layer increased.

The temperature of the active layer in the study area also changed in 2013–2018. Thus, at a depth of 0.1 m, the mean annual temperature varied from 2.9 to 4.4 °C. The soil temperature during the year at a depth of 0.1 m ranged from –21.3 to 24.4 °C. During the period of monitoring, high temperature values in

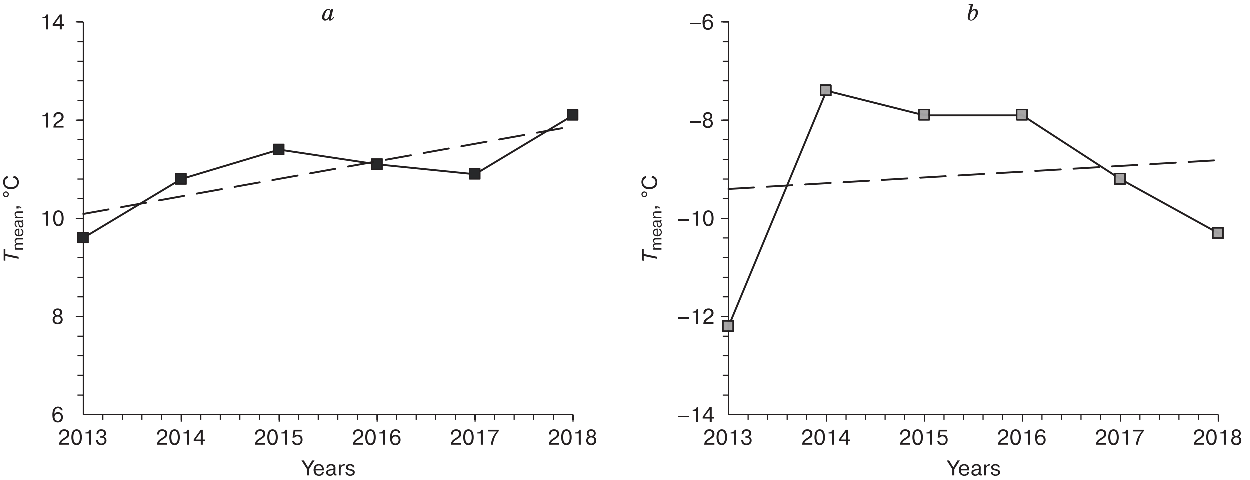

Fig. 3. The mean seasonal air temperature T_{mean} during the warm (*a*) and cold (*b*) seasons in the study area.

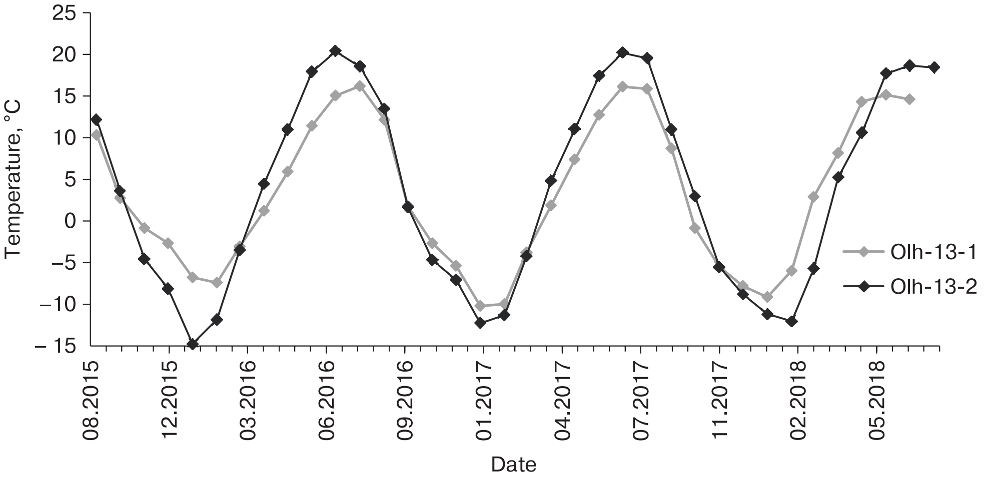

Fig. 4. The mean monthly temperatures at a depth of 0.1 m in the areas with permafrost (borehole Olh-13-1) and unfrozen ground (borehole Olh-13-2).

the annual cycle and a shift towards a positive gradient indicate the additional warming of soils on the surface.

In 2018, within the permafrost area (borehole Olh-13-1), the annual amplitude of soil temperatures at a depth of 0.1 m was 29.9 °C (from –11.2 to 18.7 °C), whereas the annual amplitude of air temperatures reached 53.9 °C (from –31.1 to 22.8 °C). In the unfrozen area (borehole Olh-13-2), the annual amplitude of soil temperatures at a depth of 0.1 m was 44.0 °C (from –20.0 to 24.0 °C), at a depth of 0.1 m). The amplitude of the mean monthly soil temperatures at a depth of 0.1 m ranged from –10.2 to 16.2 °C for the permafrost area, and from –14.8 to 20.4 °C for the unfrozen area (Fig. 4).

A significant difference between soil temperature ranges at the frozen and unfrozen sites attests to the high thermal resistance of permafrost (i.e., the need to spend more energy to warm up the soil), as well as to a higher sensitivity of unfrozen ground to changes in the air temperature. The water content of soils and vegetation conditions have an additional impact. Vegetation is denser in the area with permafrost development and protects the soil from temperature changes both in summer and in winter. The seasonally thawed layer in the area with permafrost freezes more intensively, and the transition through 0 °C proceeds quicker.

The annual amplitude of temperatures at a depth of 2.0 m within the seasonally thawed layer (borehole Olh-13-1) is 13.8 °C (from –4.3 to 9.5 °C). As noted earlier, permafrost in this area was found at a depth of 1.9 m. As the drilling was carried out in August, the thawing depth in the borehole somewhat increased, and subzero temperatures at a depth of 1.9 m were established only in January (Fig. 5).

In the area of unfrozen ground (borehole Olh-13-3), the temperature at a depth of 2.0 m drops to 0 °C. However, below this depth, it remains in the positive range. Thus, this depth indicates the maxi-

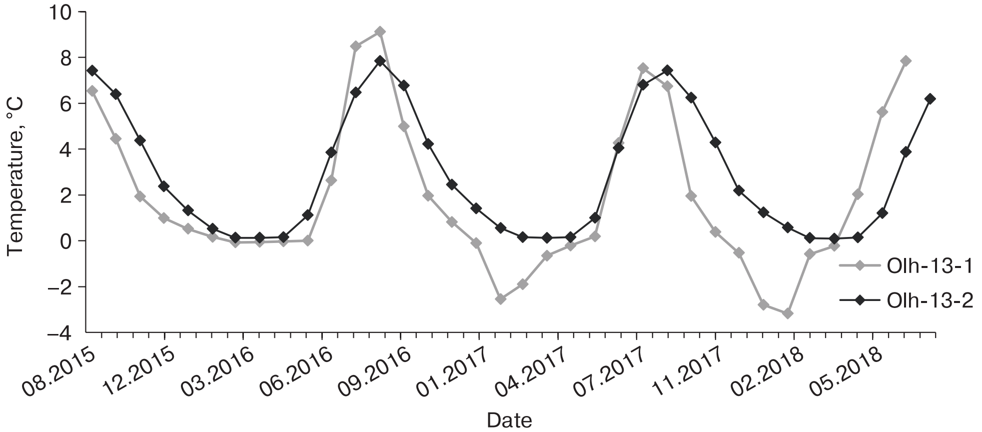

Fig. 5. The mean monthly temperature at a depth of 2.0 m in the areas with permafrost (borehole Olh-13-1) and unfrozen ground (borehole Olh-13-2).

mum depth of seasonal soil freezing. The annual amplitude of temperatures at this depth in the area with unfrozen ground reaches 7.9 °C (0.1 to 8.0 °C).

The mean annual soil temperature at a depth of 2.0 m, within the active layer of both plots (with and without permafrost) in the steppe zone of the Baikal region was steadily rising during the monitoring period. Thus, in borehole Olh-13-3 (unfrozen ground), the mean annual temperature soil temperature at this depth (within the seasonally freezing layer) increased from 2.6 to 3.0 °C. The temperature below the seasonally freezing layer also increased; at a depth of 9.3 m, the mean annual temperature was 1.8 °C in 2013 and 2.4 °C in 2018 (Fig. 6).

The mean annual soil temperature at a depth of 2.0 m, within the seasonally thawing layer in the area with permafrost (borehole Olh-13-1) varied from 2.0 to 2.1 °C, which was higher than the data published earlier [*Leshchikov, 1978*].

The mean annual soil temperature at a depth of 3.5 m during the study period in the permafrost area (borehole Olh-12-1) increased from –0.1 to 0.7 °C, which indicates an increase in the depth of seasonal thawing from 2.5–3.0 m to more than 3.5 m in the area with isolated permafrost patches in steppe landscapes of the Baikal region (Fig. 7).

Within the steppe area, previous geocryological studies were conducted in 1984. Initial observations demonstrated that the mean annual temperature of permafrost ranged from –0.1 to –0.2 °C, and the total water content was in the range of 30–40 %. Permafrost table was found at a depth of 2.0–2.5 m [*Leshchikov et al., 1984*]. During the study period from 2013 to 2018, the general trend of changed in the mean annual temperature was close to the regional trend of changes in the air temperature in the region, the main factor affecting regional soil temperatures.

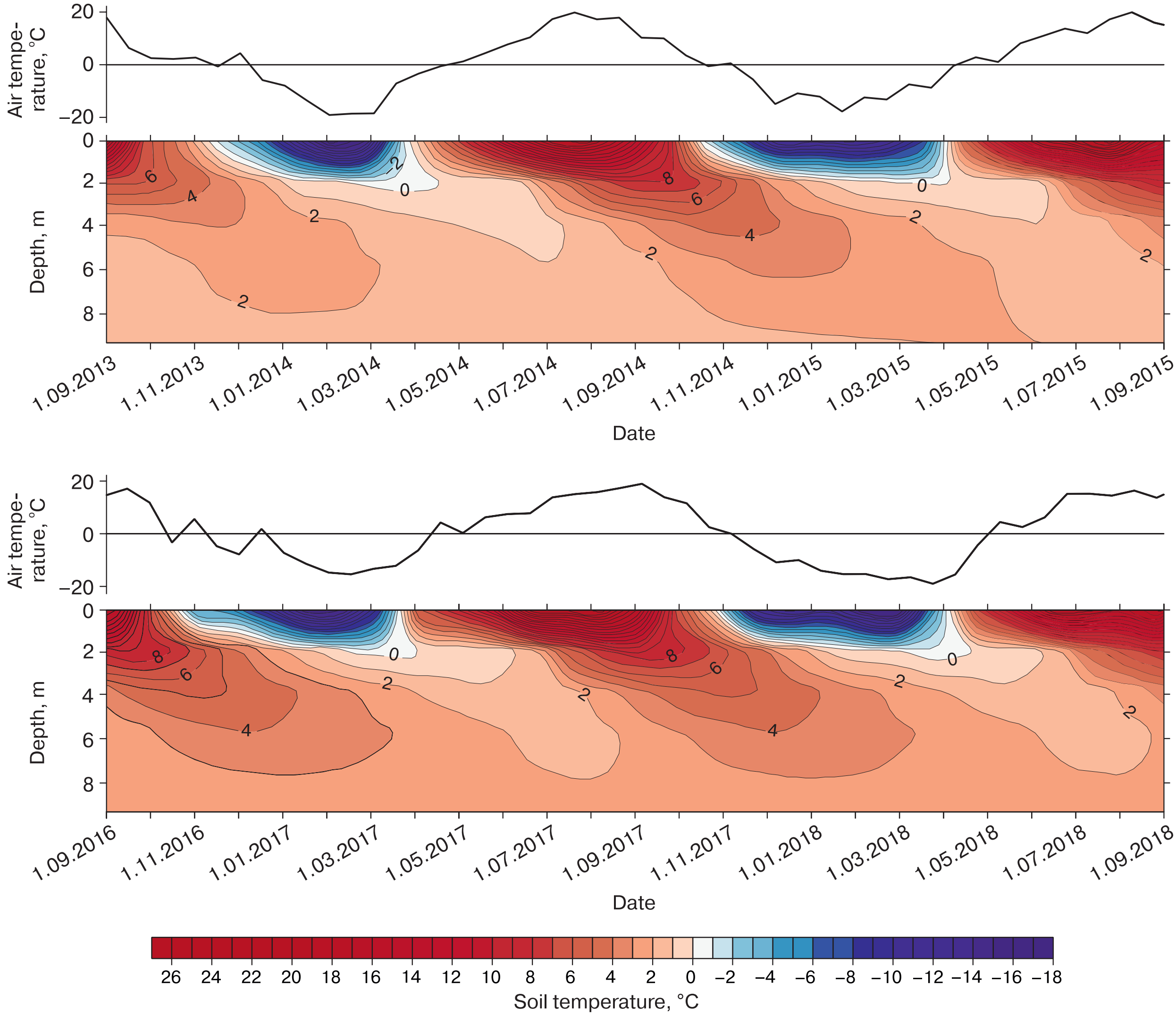

Fig. 6. Thermoisopleths of soils, borehole Olh-13-3.

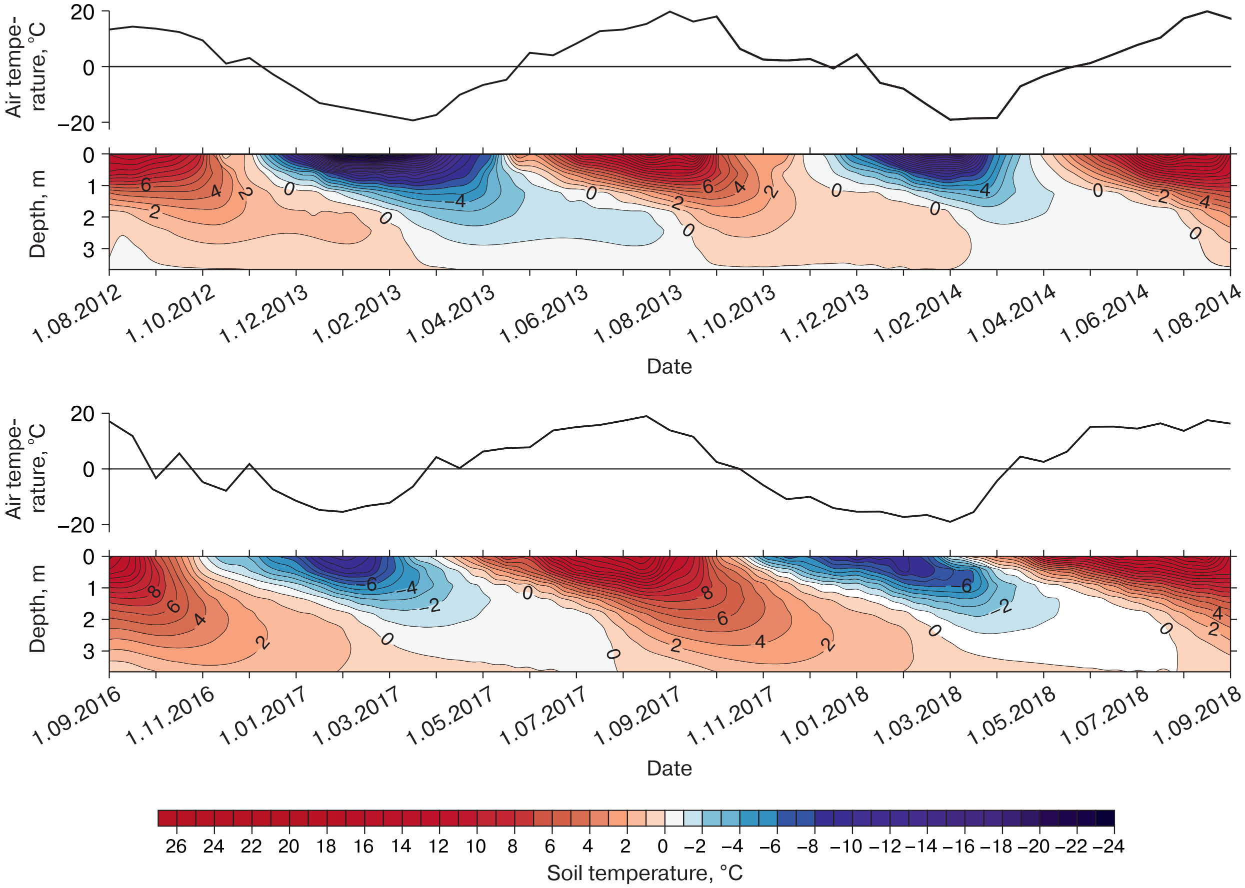

Fig. 7. Thermoisopleths of frozen soils, borehole Olh-12-1.

DISCUSSION

The temperature regime of permafrost is transformed under the current trend of the air temperature. The change in the soil temperature is largely related to the modern rise in the air temperature. The influence of the secondary factors (precipitation, vegetation cover, moisture) has led to additional warming of soils and local thawing of permafrost.

Olkhon Island is characterized by insufficient atmospheric moistening. The annual precipitation varies from 197 to 278 mm, and the ratio of annual precipitation to the total evapotranspiration is 0.34. Most of precipitation falls during the three summer months. In winter, monthly precipitation does not exceed 5 mm and the snow cover thickness does not exceed 10–15 cm [*Imetkhenov et al., 1997; Pellinen, 2018*], which is insufficient to moist the surface soil layer. The soil water content on the plot with unfrozen clayey sediments (boreholes Olh-13-2 and Olh-13-3) reaches 4.5 and 6.3 %, respectively, in the upper part of the profile (0–1 m) and increases to 29.2 and 27.0 % at the depths up to 4.0 m. Vegetation on the surface does not form the dense cover and, therefore, the summer heating of the surface soil is intense.

On the plot with permafrost (boreholes Olh-12-1 and Olh-13-1), the water content of clayey sediments in the upper layer varies from 23.4 to 30.7 %, which is comparable with the data obtained several decades ago [*Leshchikov et al., 1984*]. An increased water content creates more favorable conditions for the formation of a stable vegetation cover. This is the reason for the difference in the amplitudes of temperatures in the surface soil layers in the annual cycle at the plots with permafrost and unfrozen soil (Fig. 4). During the cold season, before the establishment of subzero temperatures on the surface, the amount of atmospheric precipitation decreases and the remaining water migrates towards the top of permafrost. Thus, soil freezing begins at low values of the water content in the surface soil layers. An abnormally high for clayey soils value of seasonal soil thawing in borehole Olh-12-1 is apparently explained by a relatively low soil water at the initial stage of thawing. The low water content in the surface soil layer contributes to a greater soil warming and deeper soil thawing. Taking into account a continuous rise summer temperature, the changes in the soil temperature regime occur both in the active (seasonally thawed) layer and in the underlying permafrost. During the study period, the mean annual soil temperatures display a positive trend throughout the section. This is related to the changes in the air temperature against the background of insignificant precipitation and the low soil water content.

Seasonal freezing on the plot with unfrozen soil occurs intensively; however, as winter air temperatures remain relatively high, the depth of soil freezing does not reach 2.0 m. The thawing of seasonally frozen soil layer in the steppe zone on the plot with unfrozen soil proceeds without delay, because the snow cover is very thin, and the vegetation cover is poor and weakly protects the surface from warming. In combination with a low soil water content, thermal conductivity of the soils increases, and the soil layer frozen in winter thaws out quickly in May; then, it is subjected to a gradual warming and remains in the thawed state almost until November (Fig. 6).

During the observation period from 2012 to 2018, the soil temperature within the active layer on the plot with permafrost (borehole Olh-12-1) displayed a trend toward gradual rising. In 2012, permafrost temperature at a depth of 3.5 m was in the subzero range (from 0 to –0.1 °C), which was slightly higher than that in the 1980s [*Leshchikov et al., 1984*]. In 2015, there was a transition from subzero to abovezero values: the maximum temperature at a depth of 3.5 m reached 1.3 °C. In 2017–2018, the maximum soil temperature at this depth was already 1.7 °C.

Changes in the temperature regime of permafrost are associated with a general increase in the ambient air temperature and with the low atmospheric precipitation. The soil water content on the plots with permafrost is higher than that on the plots with unfrozen soil. However, owing to the downward migration of moisture migration towards the underlying permafrost table, the soil freezing from the top occurs without significant delay and proceeds to the full depth of the soil thawing. The mean annual soil temperature on the plot with permafrost varies from –0.3 to 1.3 °C. The active layer, thawed in summer, completely freezes in winter. Under the conditions of constantly increasing temperature both in the warm and cold periods, the soil thawing depth reaches 3.5 m. If the current trend for temperature rise, insufficient atmospheric moistening, and changes in the soil water content on the plots with permafrost is preserved, we can expect the formation of taliks and permafrost degradation in the steppe landscapes of Olkhon Island.

Compared to other areas in the Baikal region, permafrost on Olkhon Island is under high stress related to the current climate change. Therefore, the Olkhon station organized by the Institute of the Earth's Crust of the Siberian Branch of the Russian Academy of Sciences should be maintained and developed as one of the reference points for monitoring the natural state of permafrost at its southern boundary.

CONCLUSIONS

Permafrost at the boundary of the southern geocryological zone is subjected to significant transformation under the influence of climate change. In the study area of the steppe region of Olkhon Island, the ambient air temperature demonstrates a positive trend. From 2013 to 2018, annual air temperature increased from –1.2 to 1.7 °C. The main growth took place in the summer period, owing to which the surface soil warming became more intense.

The mean annual temperature of unfrozen soil also demonstrated the rise throughout the entire massif; the depth of soil freezing on this plot did not exceed 2.0 m. The soil temperature on the plot with permafrost also increased, which contributes to degradation of high-temperature permafrost in the zone of isolated patches of permafrost. The thawing depth lowered deeper than 3.5 m, and the mean annual temperature increased to 1.7 °C.

Migration of moisture has a significant influence on the temperature regime of soils in Olkhon Island. The water content in the areas of unfrozen soil in the near-surface layer is 4.5 and 6.3 %, which accelerates the soil freezing, and the phase transition occurs without delay. In the areas with permafrost, the soil water content is higher and varies from 23.4 to 30.7 %. However, due to migration of moisture to the top of permafrost and the positive trend of air temperature, soil thawing reaches the maximum values and contributes to the formation of taliks.

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