Geographical regularities of the permafrost-thermal regime of soils in Transbaikalia

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Abstract. We have estimated the freezing-thermal regime of Transbaikalia soils qualitatively and quantitatively. Perennial permafrost almost throughout the region makes such an estimation of the thermal condition of the soils rather topical in terms of the region’s climatic resource. We have attempted to determine and classify thermo-freezing regime of the soils for entire Transbaikalia and show the general geographical characteristics of the thermal regime of winterly Transbaikalia. The studies of the 3.2-m thick soil layer were based on the perennial data of 49 meteorological stations. For the analysis of the thermo-freezing regime of the soils, we used the mean monthly values of the smallest temperature at the standard depth of the soil profile. The entire array of the temperature data was divided into five grades of different widths and represented in the form of vertical profiles. The steps of the scale reflect the progressing increase in winter cooling of the entire soil layer. The weakest soil cooling is observed for the eastern shore of Lake Baikal: these are the moderately cold conditions. In the southern closure of the Barguzin depression, the state of the soil thickness transits smoothly from moderately cold to cold conditions. Very cold soil conditions are propagating from southeast to northwest in the perennial permafrost zone. Severe conditions of soil are present in local regions of the southern part of the territory and its northern part where the sandy-loam soil with pebble admixture allows perennial permafrost to lie at small depths. Extreme severe conditions mainly occupy the races of total perennial permafrost.

1. Introduction
Transbaikalia lays in the southeast of East Siberia far away from seas and oceans. It has a complicated relief of intermitting mountains and lowlands. These determine the Transbaikalia climate. The severe climate within the region is harsh continental and contrasting. Coast of Lake Baikal stands out of the rest of the region. There numerous scientific publications about regional tendencies for climate formation and its peculiarities. The studies of the climatic resources in the second part of the past and beginning of the current centuries has been related to the intensified industrial activity in the northern Transbaikalia as well as with a search for an eco-industrial strategy for the Baikal region development [1-5].

The studies of Transbaikalia climatic resources paid, however, little attention to the thermal regime of soils. Its quantitative estimation in terms of the climatic resource is meanwhile rather topical due to the Perennial Permafrost (PP), covering almost all the considered territory [6, 7, 4]. Such an indicator of the soil thermal condition as its temperature can be considered an integral characteristic of climatic resources of the territory since the solar energy is actively transformed and accumulated in the soil by the heat exchange processes in the soil itself and the system: the near-ground air – the ground surface.
– the soil – the soil-forming substance. Thermal regime in the 3.2-m thick soil (soil-ground) layer and the geographical characteristics of its current conditions in the Transbaikalia territory are indicated in [8]. These publications, however, give an only fragmentary description of the wintry thermal resources of the soil layer. Our studies are, therefore, aimed to determine and classify the thermal-freezing regime characteristics of soils on the entire territory of the Transbaikalia. Based on the study, general geographic tendencies will be determined, and the results will be presented in the form of maps.

2. Materials and methods
Our analysis of the wintry thermo-freezing regime in the 3.2-m thick soil layer was based on the perennial data from meteorological station network of the Transbaikalian Administration of Hydrometeorology and Environmental Monitoring. The records of 49 stations that monitor the soil temperature were used. The stations of the instrumental monitoring are mainly located in open regions of valley-basin complexes, highland plains and on the Lake Baikal coast. The soil temperature data from meteorological stations of the Russian Federation [9], as well as more bulky data on the Transbaikalia territory [8], were subjected to an essential preparatory correction.

The study of the soil thermo-freezing regime relied on the analysis of the monthly means of the smallest temperature at a standard depth of the soil profile. Since the instant of the smallest temperature onset in annual cycles is unstable, it was selected individually for each year of the long-term series. In Transbaikalia, the temperature distribution over the vertical profile and with the horizontal position is rather specific. The depth variation corresponds to the radiation type characteristic of the winter season (the temperature increases with depth). Though the vertical temperature profiles are everywhere curvilinear, the positive drops in the soil temperature (upward heat flux) show considerable quantitative variations within the region. It largely depends on whether the soil layer is sub-layered by a melted or frozen ground (as well as on the depth at which the ground lays), mechanical composition and structure of the soil, and other factors of influence. Naturally, the important role of the climatic (external) factor in the temperature drop formation inside the soil layer cannot be also ignored. Considerable differences in the drop between different soil layers were indicated. A relatively large drop in the temperature was observed in the upper layer, and it decreased considerably with depth.

A distinguishing property of spatial variations of the lowest soil temperature is its rather low negative value in the upper soil levels, which are typical of many locations within the considered territory (even in its southern part). This phenomenon is due to the influence of climatic factors on the soil temperature: cold winter and small thickness of the snow cover. The soil temperature at the depth of 3.2 m is positive only on the eastern coast of the Lake Baikal; negative values dominate in the rest of the territory.

3. Results and discussion
Considering the properties of the soil thermal regime, we have adapted the analytical methods developed for territories of different relief for application to complicated reliefs and permafrost of Transbaikalia. The extension and specification of the method consist in a separation of the entire mass of data on the minimum temperature of the soil layer (represented in the form of vertical profiles) into ranges of different widths, which are distinguished by their quantitative values and the character of their depth. This comprises the classification scheme for the thermal regimes of soils. The temperature of the lower part of the soil layer is of primary importance for the determination of the number and widths of the ranges. The ranges are classified by quantitative and qualitative estimation of the soil wintry cooling. The depth of seasonal freezing and duration of the negative temperature in the soil profile were additionally attributed to the classification features. The data obtained are related to a certain place (measuring location) within the region. In the form of a map, the information reflects general tendencies of Transbaikalia differentiation by a certain characteristic.
Among thermal characteristics, which control the soil thermal regime in the warm season, the near-surface air temperature is of primary importance. For the cold season, the air temperature and thickness of the snow cover are the most significant. Estimating the relative influence of various factors revealed the most influential factor. Previously, similar relations were estimated for the Irkutsk Region and the West-Siberian flatland. There was a dominating influence of the snow cover on the temperature of the upper soil layer (depths of 0.2 and 0.4 m), which corresponds to the general scheme of tendencies characteristic of Siberia [10]. However, there are other relations between the analyzed factors in the Transbaikalia. The relation between the temperature of the upper soil layers and thickness of snow cover largely depends on the landscape geographical factors. Two regions of the relation, east coast of Lake Baikal (red circles) and the rest of Transbaikalia (blue diamonds), are pronounced in the correlation plane (figure 1).

![Figure 1](image)

**Figure 1.** Scatter plot of the soil temperature (T, °C) at depths of 0.2 (A) and 0.4 m (B) as the function of snow cover (H, cm). The straight lines show the best linear fit.

The warming influence of the snow cover thickness on soils is practically absent here since the thickness in almost all locations of the soil temperature measurement is small. The winter soil temperature and its temporal variations are, therefore, mainly governed by air temperature; though this relation is rather complicated.

Low winter temperatures and relatively small thickness of snow cover result in deep soil freezing in major parts of wintery Transbaikalia. In Transbaikalia, the smallest monthly mean temperature varies in a wide range at all depths of the soil profile. It varies mainly from -2 to -21°C in the upper layer (0.2 m) and from +3 to -8°C at a depth of 3.2 m. The entire array of temperature data represented in the form of vertical profiles was divided into five grades of different widths. The grades reflect a sequential increase of winter cooling of entire soil thickness (table 1).

The weakest soil cooling is observed on the east coast of Lake Baikal. In terms of the qualitative estimation, these are the moderately cold conditions (A) with short-term and shallow (0.8-1.6 m) seasonal freezing. These can be the clay-loam soils (with pebble admixture) or sand-loam soils. The clay-loam soil on the north coast of Lake Baikal (Nizhneangarsk) also belongs to this grade; though
the slightly negative temperature can penetrate up to 2.4 m in this region. A similar thermal regime of layered soils (clay-loam – sand-loam – sand) is also found in the accumulating flatland of the Selenga River outflow. A combination of a mean air temperature of -17 °C to -20.5°C in January and 25-40 cm thickness of snow coverage corresponds to weak cooling of soils.

Table 1. Grades scale of the soils winter cooling

| Depth, m | 0.2  | 0.4  | 0.8  | 1.2  | 1.6  | 2.4  | 3.2  |
|---------|------|------|------|------|------|------|------|
| Thermal conditions | | | | | | | |
| Moderately cold (A) | -2.0 ± 7.0 | -1.2 ± 6.2 | 0.0 ± 5.0 | 1.0 ± 3.7 | 1.6 ± 2.6 | 2.6 ± 0.6 | 3.0 ± 0.5 |
| Cold (B) | -7.0 ± 12.0 | -6.2 ± 10.0 | -5.0 ± 8.4 | -3.7 ± 6.8 | -2.6 ± 3.8 | -0.6 ± 2.0 |
| Very cold (C) | -17.0 ± -21.0 | -14.4 ± -18.4 | -10.4 ± -14.4 | -7.0 ± -10.8 | -4.4 ± -7.6 | -0.8 ± -3.4 | 1.0 ± -1.0 |
| Severe (D) | -12.0 ± -16.5 | -11.0 ± -15.5 | -8.4 ± -12.9 | -6.4 ± -10.7 | -5.0 ± -9.0 | -3.0 ± -6.6 | -2.0 ± -5.0 |
| Extreme (E) | -16.5 ± -21.0 | -15.5 ± -20.0 | -12.9 ± -17.4 | -10.7 ± -15.0 | -9.0 ± -13.0 | -6.6 ± -10.2 | -5.0 ± -8.0 |

The temperature of the clay-loam soil on the boundary between the inclined plane and bottomland in the southern closure of the Barguzin depression slightly decreases. This is a characteristic case of a smooth transition from moderately cold (A) to cold (B) condition of the soil layer. In this region, seasonal soil freezing begins in November and reaches the depth of 2.4 m in March. Period of the negative soil temperature lasts for 170 and 114 days at depths of 0.2 and 1.6 m, respectively. The soil thermal regime of soils is caused by the -27.8°C air temperature in January (-23.6°C in February) and snow cover thickness of approximately 35 cm. The cold soil condition (B) corresponds to the temperature range from -7 °C to -12°C at a depth of 0.2 m and from 0.5 to -2°C at 3.2 m. They are mainly present in the southern Transbaikalia but can be locally present in its northern regions where soils are sub-layered by melted ground. The cold conditions are associated with sums of air temperature below -10°C, from -2165 to -3625, and snow cover less than 25 cm.

Soils in very cold conditions (C) have a special depth profile of temperature. In the upper layer (0.2 m), the temperature is rather low (-17°C to -21°C). The temperature increases rapidly with depth and reaches +1°C to +3°C at 3.2 m. Notably, from 1-m depth, temperature profiles of the grade C are close to the profiles of the grade B (figure 2). In this case (C), the cooling of soil is predetermined by the sums of air temperature below -10°C, from -2100 to -3600°C, and the snow cover of 5-15 cm.

These soil conditions refer to local regions of sand-loam soils with pebble admixture in the northern part as well as in the southern part of the territory where PP can be present at shallow depth. Severe conditions of soils (D) extend from southwest to northeast in the dense PP zone. They are locally inherent to those regions of southeastern Transbaikalia where PP has a patchy distribution, and seasonal soil freezing is deeper than 3.2 m.

Extreme conditions (E) of sand-loam soils with pebbles are characterized by the temperature range from -16.5 °C to -21°C at a depth of 0.2 m and from -5 °C to -8°C at 3.2 m. They are mainly present in the dense PP ground zones (the Upper Chara basin, the slopes of the Vitim River valley, and others). They
are characterized by snow cover of 12–25 cm and sums of air temperature below -10ºС, from -3450 to -4950ºС.

Figure 2. Comparison of the soil temperature ($T_{soil}$) of the grades B and C in the soil profile of 0.2-3.2 m.

4. Conclusion
In summary, we emphasize that the estimated thermal conditions in the soil layer up to the depth of 3.2 m are mainly relevant to the natural complexes of valleys and valley-troughs that are widely spread in Transbaikalia. Thermal conditions of soils of plain veld and meadow grassland relief are characteristic of its southern regions. These natural complexes are used intensively in agriculture. Therefore, the knowledge of thermal resources of the soils, which define the operation and productivity of agricultural ecosystems, is important.

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