Soil temperature field and dynamics of freezing-thawing processes in the south of the Vitim Plateau (Transbaikal region)

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Abstract. The results of geographic and stationary studies of temperature, water and permafrost regimes and soil properties in the south of the Vitim Plateau (Transbaikal region) are discussed. Instrumental data on soil temperature regimes indicate the dynamics of soil freezing–thawing processes and attest to changes in the thawing depth of permafrost-affected soils. The revealed spatiotemporal patterns of soil freezing/thawing reflect the distribution of heat and cold (permafrost) in the soils of the studied cryoarid landscapes. Seasonal, annual, and long-term differences in the soil temperature field cause a great heterogeneity of soil toposequences with contrasting soils on the north– and south-facing slopes. An increase in the soil thawing depth has been observed over the past 50 years. In the relatively wet and cold 1970–1990 years, its rate varied from 1.0 to 1.5 cm/year with higher values typical for Haplic Chernozems under meadow-steppe vegetation, and lower values for Phaeozems under forest vegetation. Over the recent 25 years, the rate of the increase in the soil thawing depth for the same soils has intensified by 2.5–3.0 times in relation to aridization and climate warming.

1. Introduction
About 65% of the territory of Russia lies in the permafrost zone. Most of the Transbaikal region is characterized by periglacial pedogenesis, i.e., soil formation under permanent or durable contact with ice-rich sediments, subzero mean annual temperatures, high continentality of the climate, and high annual heat fluxes [1, 2]. The southern boundary of the permafrost zone runs along the south of the Vitim Plateau and the north of the Selenga Mountains [3] (figure 1). In this transitional zone from continuous to isolated permafrost, the dynamics of the soil temperature field (STF) related to global and regional climate changes are clearly pronounced.

The concept of STF was introduced by geocryologists [4] to describe the spatiotemporal distribution of temperature in rocks. The spatiotemporal patterns of STF and their significance for pedogenesis were thoroughly discussed by O.V. Makeev and his followers [5–10]. Geographical, physical and thermal properties of soils, spatial and temporal variability of soil temperature, the role of STF in soil formation were considered. At present, on the basis of new instrumental data [11–13] and long-term databases [14, 15], it becomes possible to estimate the dynamics of changes in soil temperatures near the southern boundary of permafrost in the Transbaikal region. In the past century, the thawing depth of permafrost-affected soils in the south of the Vitim Plateau has increased by about 100–140 cm in dependence on the particular soil and landscape conditions [16–19]. The maximum increase is typical for open steppe
areas near the lakes, and the minimum increase is typical for mire and wet meadow ecosystems. Soils of taiga landscapes occupy a transitional position.

![Map of the distribution of permafrost types](image)

**Figure 1.** Map of the distribution of permafrost types [3] and the location of key study sites (a); an example of the cartographic method of investigation (b).

In this study, the results of geographical and stationary studies of soil toposequences (catenas) in the mountainous Transbaikal region are presented. The particular attention is given to the STF and its development as related to global climate change; on the basis of instrumental studies of soil temperature regimes, the dynamics of changes in thawing depths of permafrost-affected soils and soil freezing depths of cold soils are analyzed.

2. **Study objects and methods**

Soil toposequences at the junction of the Yeravna permafrost forest-steppe and the Uda dry-steppe area with seasonally freezing soils have been studied. The intermediate position between two contrasting landscapes complicates the soil cover patterns on the slopes (figure 2). Soils are formed under conditions of long cold winters and relatively short dry and hot summers; the mean annual air temperature is from −3.0 to −4.1 °C, and the mean annual precipitation is 225–410 mm. The gentle north-facing slope is covered with birch–larch woodland and meadow steppes, and the steep south-facing slope is under cryoxerophytic steppe. The parent materials are represented by the weathering products of Neogene–Lower Quaternary basalts.

The studied polygon-transect (PT) was laid according to the principles of complex ordination by Sochava [20]. The soils were classified according to the new Russian soil classification system [21], the field guide for soil correlation [22] and the international WRB system [23].

The specificity of stationary field studies consisted of synchronous measurements of soil temperatures at different geomorphic positions with the use of Savvinov thermometers and resistance electrothermometers. In the warm season, measurements were carried out for twenty-four hours every 5–10 days. The soil water content on the same days was gravimetrically determined via drying soil samples at 105 °C. Auger soil samples were taken from each 10-cm-thick layer within the upper meter.
and from each 20-cm-thick soil layer in the deeper part of the profiles; the topmost 20 – 30 cm of permafrost were also sampled.

The role of topography in redistribution of precipitation and potential evaporation was assessed for the studied soil toposequences. Evaporation from the water surface (potential evaporation) was measured with a GTI-3000 vapor meter and microevaporators; a Tretyakov’s precipitation gauge and precipitation microgauges were used to measure precipitation. Field observations were carried out from May to October, every ten days. Standard tools (vapor meters and precipitation gauges) were installed on the watershed in three replicates. Precipitation microgauges and microevaporators were exposed in three replicates on different topographic elements. The obtained indicators were compared with the meteorological data of the nearest weather station with standard equipment (Sosnovoozersk weather station, Yeravnin district of the Republic of Buryatia). The observation data are within the admissible error (10%). The results for the eluvial (watershed) position were compared with the data obtained on the slopes; precipitation and potential evaporation at the eluvial position were calculated, and coefficients of precipitation redistribution and potential evaporation in the slope positions were obtained.

Figure 2. Soil cover and geomorphological profile (along the A–B line) of the polygon-transect.

The soil physical properties were studied by routine methods [24]. The depth of soil freezing/thawing was determined experimentally by a permafrost drill. The chemical properties of soils were determined according to the methods accepted in Russia [25].

To measure the potential evaporation in different geomorphic positions, preliminarily calibrated microevaporators-graduated cylinders were used. Their calibration was performed with a standard GTI-3000 vapor meter accepted in hydrometeorology. A series of parallel experiments made it possible to find correction factors and determine the potential evaporation with an acceptable error of about 10% or slightly higher, which is typical for the standard device. To reduce the effect of inevitable uneven installation of graduated cylinders on the results, the measurements were performed in triplicate at each observation point. Precipitation was measured using micro-pluviographs – measuring cylinders with a funnel, that were also verified using a standard precipitation gauge and supplied with a corresponding correction coefficient.
To understand the spatiotemporal variability of the soil climate, soil temperature and water content measurements were performed on the studied PT along five 800–m–long transects from the thalweg in the southern part across the south-facing slope, the divide (eluvial part), and the north-facing slope to the next thalweg in the north. The soil temperature was measured with a transistor thermal probe at a depth of 20 cm; the soil water content was determined in the layer of 10–20 cm. The measurement points were spaced apart at 20 m.

This scheme of field studies was designed as a practical realization of the method of complex ordination; it proved to be efficient in the study of spatiotemporal patterns of soil functioning under contrasting landscape conditions.

3. Results and discussion

The influence of topographic position on soil formation, soil properties, and dynamics of soil regimes is considered for cryoarid catenas at the junction of the Vitim Plateau and the Selenga Mountains (Transbaikal region). Instrumental studies of the temperature, water and permafrost regimes of soil toposequences have been performed since the 1970s [26].

Data on the distribution of precipitation by the elements of mesotopography, taking into account vegetation communities (table 1) are in agreement with the earlier results by Mikhailenko obtained for the southern taiga of the Transbaikal region [27]. Significant water retention (up to 10–15% of precipitation) by tree crowns was noted for the northern slopes of the Khamar–Daban Ridge [28]. As for other (open, non-forest) parts of the studied soil toposequences, the differences in precipitation between them are within 2–4% and do not exceed the permissible error.

In the first half of summer, the maximum in the soils of the middle part of the south-facing slope (SFS) and a minimum in the soils under the birch-larch forest within the trans-eluvial part of the catena on the north-facing slope (NFS).

The calculated coefficients of precipitation redistribution relative to the eluvial part (precipitation in the eluvial part was taken as a unity) clearly indicate the retention of some part of rainfall by tree crowns in the birch–larch forest. The amount of precipitation intercepted by tree crowns is about 11% of the total precipitation in the first relatively dry part of summer and 13% in the second wet part of the summer. Overall, about 12% of rainfall during the growing season is intercepted by tree crowns (table 1).

The redistribution of potential evaporation varies greatly in dependence on the topography and the particular month of the growing season. In the first half of summer, the difference between potential evaporation at the NFS and SFS reaches 85%; in the second (wet) half of summer, it increases up to 123% and then slightly decreases (to 110%) in the early fall season. In general, during the growing season, the topography, as a factor of insolation redistribution, increases the potential evaporation in the transit part of SFS by 19% and reduces it by 17–19% in the NFS; under the birch-larch forest, the potential evaporation is reduced by up to 87%.

The coefficients of precipitation redistribution and potential evaporation were taken into account in calculation of the humidity factor (HF) [29] showing the degree of climatic humidity/aridity. Data attest to considerable variations in HF by different months and elements of topography. Thus, the soils of NFS are developed under conditions of sufficient moistening, especially under the birch-larch forest, and the soils of the transit part of SFS are developed under conditions of obvious aridity.

The obtained experimental data on the atmospheric climate (precipitation and potential evaporation) and the calculated redistribution coefficients for different parts of the studied soil toposequences attest to a great heterogeneity of the studied landscapes parts in terms of these indices and completely different conditions of soil formation.

Large-scale soil mapping of the studied PT indicates sharp contrasts of soils within its different parts [10, 30]. Stagnic Phaeozems (Tonguic) are formed on the divide and adjacent NFS under the sparse larch-birch forest N 52° 28' 02.3", E 111° 04' 06.9", 893 m a.s.l.). Haplic Chernozems (Protostagnic, Tonguic, Turbic) are formed downwards in the middle part of the NSF slope under a forb-grassy
meadow in place of the former arable land (N 52° 28’ 06.1", E 111° 04’ 13.6", 880 m a.s.l.). Haplic Chernozems (Stagnic, Tonguic, Turbic) are developed within the lower accumulative part of the NFS under grass-forb meadow vegetation (N 52° 28’ 14.6", E 111° 04’ 35", 865 m a.s.l.). Eutric Cambisols (Protocalcic) under the middle part of a steeper (6–8°) SFS under sparse forb–grassy vegetation with xerophytic species (N 52° 27’ 56.1", E 111° 03’ 59.3", 890 m a.s.l.).

These soils differ sharply in their morphology, properties, and regime characteristics. Stagnic Phaeozems of the divide are characterized by the high content of gravels, low thickness of the humus horizon, low heat supply and moderate water capacity. Chernozems of NFS are wetter and have a heavier texture, especially within the accumulative (footslope) part of the catena. Cryoarid soils of the middle part of SFS have the highest content of gravels and the highest heat supply. They are characterized by a relatively coarse texture of fine earth, low humus content, and low soil water storage.

Table 1. Coefficients of precipitation redistribution and potential evaporation by topographic elements.

| Position in relief, vegetation type | Early summer (May – June) | Mid summer (July – August) | Early autumn (September – October) | Whole growing season |
|------------------------------------|----------------------------|---------------------------|-----------------------------------|---------------------|
| Eluvial position, forest-steppe     | P^a: 1.00 PE^b: 1.00 HF^c: 1.00 | P^a: 1.00 PE^b: 1.00 HF^c: 1.00 | P^a: 1.00 PE^b: 1.00 HF^c: 1.00 | P^a: 1.00 PE^b: 1.00 HF^c: 1.00 |
| Transit part of SFS^d, cryo-xerophytic steppe | 1.03 PE^b: 1.13 HF^c: 0.91 | 1.01 PE^b: 1.01 HF^c: 0.72 | 1.04 PE^b: 1.14 HF^c: 0.82 | 0.97 PE^b: 1.19 HF^c: 0.82 |
| Accumulative part of SFS^e, meadow steppe | 0.95 PE^b: 0.94 HF^c: 1.01 | 0.95 PE^b: 0.99 HF^c: 0.96 | 0.98 PE^b: 1.03 HF^c: 0.56 | 0.96 PE^b: 0.99 HF^c: 0.97 |
| Trans-eluvial part of NFS^f, birch-larch woodland | 0.89 PE^b: 0.28 HF^c: 3.18 | 0.87 PE^b: 0.08 HF^c: 10.88 | 0.89 PE^b: 0.04 HF^c: 12.25 | 0.88 PE^b: 0.13 HF^c: 6.77 |
| Trans-accumulative part of NFS^f, meadow steppe | 0.98 PE^b: 0.80 HF^c: 1.23 | 0.98 PE^b: 0.70 HF^c: 1.40 | 0.97 PE^b: 0.92 HF^c: 1.05 | 0.98 PE^b: 0.81 HF^c: 1.21 |
| Accumulative part of NFS^f, meadow steppes with halophytes | 0.99 PE^b: 0.80 HF^c: 1.24 | 0.98 PE^b: 0.77 HF^c: 1.27 | 0.98 PE^b: 0.92 HF^c: 1.07 | 0.98 PE^b: 0.83 HF^c: 1.18 |

^a Precipitation.
^b Potential evaporation.
^c Humidity factor (P/PE).
^d South-facing slope.
^e North-facing slope.

The analysis of the regime characteristics attests to the spatialtemporal heterogeneity of the temperature, water, and soil freezing–thawing regimes within the studied soil toposequences (figure 3).
The results of a continuous soil temperature survey indicate a clear differentiation of the soil cover with respect to the heat supply (figure 3A). There is a constantly low heat supply of Stagnic Phaeozems under the sparse birch-larch forest on the divide. Soil temperatures reach the range of biologically active temperatures (> 10 °C) only in the early July. On the slopes, the soil temperature at a depth of 0.2 m reaches 10.7 °C already in the 20s of May. Permanently cold temperatures are typical for Stagnic Chernozems within the accumulative part of the catena on the NFS. Soil warming reaches its maximum within the eluvial and transit parts of the SFS, where soil temperatures at a depth of 0.2 m depth reach its maximums (18.5–20.1 °C), and the soil temperature above 10 °C is maintained until the first days of October.

The analysis of the spatiotemporal variability of soil water content attests to the presence of zones with different moisture availability in dependence on the topographic position (figure 2B). The most arid conditions are characteristic of the transit part of the SFS, where the soil water content in summer decreases to the wilting point. The soils of the eluvial (divide) position–steppe variants of raw–humus burozems (Stagnic Phaeozems) – are no less desiccated. The same soils under the forest in the upper part of the NFS have a better water supply than the soils on the SFS. The highest water supply during the entire growing season is typical for the fine-textured soil in the trans-accumulative and accumulative landscape positions, especially on the NFS.

With respect to permafrost-affected and cold soils, the notion of the cryogenic regime implies the intensity of soil freezing and thawing processes and their spatiotemporal patterns. Comparative characteristics of thawing processes in the studied soils demonstrate that stable thawing begins in late April–early May in the eluvial and transit parts of the SFS (figure 2C). By May 10, the thawing depth in Stagnic Phaeozems and Eutric Cambisols of the SFS reaches 54–60 and 100–105 cm, respectively. Haplic Chernozems (Stagnic) on the NSF thaw by this time to a depth of 50–55 cm. Stagnic Phaeozems under forest vegetation still remain in the frozen state.

![Figure 3. Spatiotemporal heterogeneity of (A) temperature, (B) water, and (C) soil thawing regimes on the studied polygon.](image-url)
does not exceed 0.3–1.4 cm/day. A short-term stabilization of the thawing depth takes place in late September-early October.

This period is characterized by the maximum depth of thawing. Stagnic Phaeozems have the zero isotherm at a depth of 270–280 cm under the birch–larch forest and at a depth of 275–280 cm under the steppe. Being involved into agricultural use, these soils thaw to a depth of 290–300 cm.

The soils of the transit part of the SFS (Eutric Cambisols) are subjected to seasonal freezing to a depth of 380–400 cm. The minimum thawing depth in the soils underlain by permafrost is in the constantly wet heavy-textured Haplic Chernozems (Stagnic): 270–275 cm. Haplic Chernozems (Protostagnic) thaw to a depth of 290–300 cm. The thermal impact of runoff water from a higher hypsometric level causes an increase in the thawing depth within the accumulative part of the catena on the NFS.

As a rule, the soil freezing begins from the top of Stagnic Phaeozems under forest in the first third of October. The velocity of soil freezing is 2.0–2.5 times higher than the velocity of soil thawing. Soil cooling and freezing from the top are accompanied by the slow freezing from the bottom. After the merging of seasonal frost with permafrost, intense soil cooling takes place in December and January.

Comparison of soil temperature fields on the NFS and SFS shows considerable differences between them. These spatiotemporal variations in the soil temperature reflect the distribution of heat and cold (permafrost) in the studied soil catenas and can be called the mirror image of soil freezing/thawing processes. To illustrate it, compare the soil temperature isopleths derived from temperature measurements in the middle parts of NFS and SFS. Haplic Chernozems (Protostagnic, Tonguic, Turbic) of the NFS are subjected to seasonal thawing for 4.9–5.0 months in summer, while their lowermost horizons (at a depth of about 3 m) remain frozen. On the contrary, Eutric Cambisols (Protocalcic) of the SFS remain in the frozen state for 5.8–6.0 months, whereas their lowermost horizon is in the thawed state almost throughout the year. Spatiotemporal variations in the distribution of “heat” and “cold” (subzero temperatures, frost) look like mirror images of one another (figure 4).

![Temperature and permafrost regime and "mirror image" of soil freezing/thawing processes.](image)

**Figure 4.** Temperature and permafrost regime and "mirror image" of soil freezing/thawing processes.

Analysis of data on the soil thawing depth over the past 50 years shows that it increased at a rate of about 1.0–1.5 cm/year depending on the soil position in the catena in the relatively humid and cold years of 1970–1990. Higher values were typical for Haplic Chernozems under meadow-steppe vegetation, and smaller values were typical for Phaeozems under forest vegetation. In the recent 25 years, the rate of soil thawing has increased by 2.5–3.0 times because of aridization and warming of the climate.

4. **Conclusions**

The role of the topographic factor in the precipitation redistribution and potential evaporation has been quantitatively evaluated for soil toposequences in the south of the Vitim Plateau. The birch–larch forest
crowsns intercept from 11% (during the relatively dry first half of summer) to 13% (during the wet second half of summer) of precipitation; in general, the tree crowns retain up to 12% of rainfall during the growing season. As a factor redistributing incoming solar radiation, the relief increases the potential evaporation in the transit part of the SFS by 19% and reduces it by 17–19% for the soils on the NFS; forest vegetation reduces the potential evaporation by 87% in comparison with evaporation from the water surface on the open level surface of the local divide.

Seasonal, annual and long-term differences in the soil temperature field cause a great heterogeneity of soil toposequences with contrasting soils on the north- and south-facing slopes. The established "mirror image" of soil thawing/freezing processes can serve as a diagnostic indicator for the separation of cold durable freezing and permafrost-affected soils.

Over the past 50 years, an increase in the soil thawing depth has been observed. In the relatively wet and cold 1970–1990, its rate varied from 1.0 to 1.5 cm/year with higher values typical for Haplic Chernozems under meadow-steppe vegetation, and lower values for Phaeozems under forest vegetation. In the recent 25 years, the rate of increase in the soil thawing depth for the same soils has intensified by 2.5–3.0 times in relation to aridization and warming of the climate.

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