Dynamics of changes in thawing and freezing depth in soils of Western Transbaikalia in different types of permafrost distribution

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Abstract. This study reveals temperature regimes of the three contrasting ecosystems in the permafrost area of Western Transbaikalia: meadow-forest ecosystem, forest-steppe and dry-steppe. Annual profile temperature data show the functioning of the studied soils in cryogenic and long-term-seasonally-freezing temperature regime. The most explanatory temperature variables are temperature penetration above 5°C at 100 cm depth and the amount of days with temperature above 0.5°C and 10°C at 20 cm, 50 cm, and 100 cm depths. Also, this work presents a comparative analysis of indicators of soil climate change and shows the spatial-temporal distribution of the reaction of the thawing and freezing depth in soils.

1. Introduction
Global climate change is the main cause for the degradation of permafrost which is especially important for the southern border of the permafrost zone in Transbaikalia. Climate change is reflected in the thermal state of the active layer (seasonally thawed layer of soil in the permafrost zone, thawing only in the warm period) [1-4].

The zoning scheme [5] shows that permafrost currently affects ecosystems on about 1/4 of the European territory and 2/3 of the Asian territory. In Buryatia, continuous permafrost covers an area of 121.21 thousand km², or 34.5% of the total area [6]. Discontinuous permafrost accounts for 31.3% (109.97 thousand km²).

The permafrost with the insular distribution is subdivided into the following gradations in terms of thickness (with the corresponding areas): 50-30 m (36.89 thousand km², i.e. 10.5%), 30-20 m (37.59 thousand km², i.e. 10.7%), less than 20 m (45.32 thousand km², i.e. 12.9%). The shares of continuous, discontinuous and insular permafrost in the geocryological structure of the territory of Buryatia is approximately the same: 34.5; 31.34; 34.1.

In this way, the research of the dynamic of freezing and thawing processes in soils on different types of permafrost is very relevant and actual with global changes and climate aridization.

2. Objects and Methods
Monitoring studies of forest-meadow landscapes were carried out to compare the soil climate, where atmospheric–soil measuring complexes (ASMC) [7] and soil recorders [8] (figure 1) were installed at the test site (TS) on different types of permafrost distribution.
Figure 1. Map of the distribution of permafrost types [6] and the scheme of the atmosphere and soil measurement complex (ASMC) locations.

Continuous permafrost is widespread within the central part of the Vitim Plateau, ‘Bagdarin’ polygon. There are soddy-cryometamorphic gley permafrost soils on the terrace above the floodplain under meadow grasses. The soil surface is hummocky, with sinks and frost cracks up to 0.02 m width. These soils have a grey humus horizon, weak subangular blocky structure, light texture, slightly acidic reaction, and low humus and moisture content in the upper horizons. From a depth of 0.15-0.20 m, heavy loamy cryometamorphic horizon is observed, moisture content increases, and signs of redoximorphism and cryoturbation appear. Permafrost is recorded at a depth of 1.90-1.95 m, and the moisture reserve (0-1.00 m) in these soils is average.

Discontinuous permafrost is in the south of the Vitim Plateau, ‘Yeravna’ polygon. Clay–illuvial quasi-gley frozen chernozems are found on the lacustrine plain of the Yeravininskaya depression under meadow steppes, with grasses and fragments of xerophytic communities. These soils are characterized by the loamy dark humus horizon with a high content of humus, a neutral pH, and a fine subangular structure. A yellow-brown heavy loamy moist carbonate horizon with a subangular and angular blocky structure begins from a depth of 0.53 (0.65) m. There are frost cracks and cryoturbations including gravel and stones throughout the soil profile. Soil moisture content increases with a depth, and the moisture reserve (0-1.00 m) in these soils is average. Permafrost is found at a depth of 2.75-2.80 m.

Sporadic permafrost is confined to the north of the Selenginskoye Middle Mountains, ‘Khurumsha’ polygon. Cryo-humus lithozems are formed under steppe vegetation on shallow crystalline rocks. The thickness of the loose horizon (AK) is 6 cm, the horizon of carbonate accumulation (Rca) is well expressed lower along the profile in the form of a powdery mass of CaCO₃ in fine fraction and abundant sintered crusts on the lower surfaces of stones. Soils seasonally freeze up to 2.2 m.

The climate of Western Transbaikalia is sharply continental with significant amplitudes of air temperature as well as a small amount of precipitation with an extremely uneven distribution throughout the year. The northern part of the study area is characterized by a severe winter climate. The average temperature is of −2.0°C in Sosnovo-Ozersk and −5.1°C in Bagdarin, which contributes to the accumulation of huge reserves of cold in soil. Moving from north to south, there is a decrease in the average annual air temperature to 0.3-0.4°C in Khurumsha. In spring, the lowest air humidity is observed at all test sites from 40% to 65% in Khurumsha.
The average annual precipitation was 438 mm in Bagdarin, 345 mm in Sosnovo-Ozersk, and 208 mm in the southern regions in Khurumsha in 2018. A characteristic feature of the atmospheric humidification regime of Western Transbaikalia is a sharply shifted precipitation maximum for the second half of summer. The water regime of soils in the first half of summer becomes scarce with such a precipitation regime: the potential moisture consumption is 5-7 times higher than the input, the moisture coefficient decreases from 0.9 to 0.2 [9]. The upper layers of soils undergo especially sharp drying, however, permafrost, which feeds the root layer during slow thawing, prevents the deeper spread of the drying front.

The duration of the frost-free period ranges from 54 days in Bagdarin to 99 in Khurumsha. The sum of average daily temperatures (≥10°C) varies from 1,191°C in Bagdarin to 1,716°C in Khurumsha.

The physical properties of soils in forest meadow landscapes were performed according to the methods [10]. Also, soil texture, volumetric and specific gravity were determined traditionally [11]. The results of the study of soils, thawing and freezing are given on the example of TS. The depth of freezing and thawing was determined using the ASMC, which characteristics are given in detail [12]. Diagnostics and classification of soils are given according to the Russian Field Guide of Soils [13] and World Reference Base for Soil Resources [14].

The reliability of APIC measurements was studied in detail in [15]; the accuracy of soil temperature sensors is 0.1°C. Measurements are carried out 8 times a day at standard meteorological dates according to [16]. According to the time range of measurements, the number of days was calculated until complete freezing and thawing, thus the depth of thawing (freezing) is divided by the number of days spent on the process, and we obtain the freezing (thawing) rate.

3. Results and Discussion

In the modern era on the territory of Western Transbaikalia, permafrost is widespread everywhere with the transition to the insular form in the south. The morphology and temperature conditions of the permafrost zone depend on the specific conditions of the relief, as the main redistributor of heat and moisture.

Among the physical properties, the particle size distribution, volumetric and specific gravity were determined. The results of the soils study, thawing and freezing of soils are given on the example of test sites.

Soils at the Bagdarin test site are developed under forb–sedge associations. The alternation of horizons can be indicated by the following sequence of indices: A0–AY–CRMg–C. Cryo-metamorphic gley CRMg horizons of dirty brownish-grey colour with rusty and grey spots and interlayers lie under the grey humus horizon (0-12 cm). Root penetration is limited to 40-50 cm. The structure becomes platy-layered towards the bottom of the profile. The total power of the soil profile is 1.3-1.5 m. The parent rock is gleyed. According to the Field Guide to Soils of Russia, the soil belongs to the type of soddy–cryometamorphic gley permafrost.

Texture of the AY horizon of the soddy-cryometamorphic gley permafrost soil is sandy loam. Cryo-metamorphic horizon with very dense light clay lies underneath it, which becomes heavy loam at the bottom of the profile (table 1).

The smallest indices of the gross density in the layer rich in organic matter are 1.12-1.50 g/cm³. A compacted illuvial horizon is below, the gross density is 1.65-1.72 g/cm³. The total porosity (50%) is satisfactory only in the upper humus–accumulative horizon, a thick stratum is below, with high moisture it is content, viscous, sticky, with unsatisfactory water permeability (36-39%). Gley processes contribute to a decrease in overall porosity, compaction and clogging of pores, which creates unfavourable conditions for subsurface drainage. In the uppermost horizons, the limiting moisture capacity is good and satisfactory only in a layer of 0-15 cm. The value of the lowest moisture capacity was 37%, and the wilting moisture does not exceed 11%, as a result, the range of active moisture is 20-26% of dry soil mass.
Table 1. Soil texture at the atmospheric-soil measuring complex test sites.

| Soil horizon.       | Fraction content, %: particle size in mm | Name          |
|---------------------|------------------------------------------|---------------|
|                     | 1-0.25 | 0.25-0.05 | 0.05-0.01 | 0.01-0.005 | 0.005-0.001 | <0.001 | <0.01 |
| O 0-1               | 4.4    | 39.8     | 40.2     | 6.0       | 8.0       | 1.6    | 15.6  | sandy loam |
| AY 1-12(15)         | 0.1    | 31.9     | 49.9     | 6.8       | 9.3       | 2.0    | 18.1  | sandy loam |
| AY wedge 20-40      | 0.0    | 24.0     | 63.3     | 5.6       | 5.8       | 1.3    | 12.7  | sandy loam |
| CRM 15-50 (80)      | 0.0    | 0.7      | 36.6     | 24.1      | 32.6      | 6.0    | 62.7  | light clay |
| CRM 90-130          | 0.0    | 3.8      | 50.3     | 15.6      | 25.2      | 5.1    | 45.9  | heavy loam |

| Soil horizon.       | Fraction content, %: particle size in mm | Name          |
|---------------------|------------------------------------------|---------------|
|                     | 1-0.25 | 0.25-0.05 | 0.05-0.01 | 0.01-0.005 | 0.005-0.001 | <0.001 | <0.01 |
| AU turf 0-5         | 12.24  | 9.22      | 53.34     | 9.24       | 8.40       | 7.56   | 25.20 | light loam |
| AU 5-15             | 20.14  | 14.96     | 33.70     | 8.32       | 12.48      | 10.40  | 31.20 | medium loam |
| AUBI 30-40          | 27.39  | 5.03      | 24.31     | 13.60      | 14.01      | 15.66  | 43.27 | medium loam |
| BI 50-60            | 17.46  | 13.74     | 16.89     | 10.30      | 16.89      | 24.72  | 51.91 | heavy loam |
| BCA70-80            | 4.43   | 8.23      | 32.96     | 14.42      | 18.95      | 21.01  | 54.38 | heavy loam |
| Q 100-110           | 4.31   | 9.60      | 34.27     | 17.14      | 15.10      | 19.58  | 51.82 | heavy loam |
| CQ 160-170          | 0.07   | 26.90     | 42.02     | 12.24      | 9.79       | 8.98   | 31.01 | medium loam |

| Soil horizon.       | Fraction content, %: particle size in mm | Name          |
|---------------------|------------------------------------------|---------------|
|                     | 1-0.25 | 0.25-0.05 | 0.05-0.01 | 0.01-0.005 | 0.005-0.001 | <0.001 | <0.01 |
| AK2-8               | 27.59  | 24.80     | 30.59     | 6.17       | 8.80       | 2.92   | 17.89 | sandy loam |
| Rca11-23            | 46.2   | 14.0      | 23.44     | 5.89       | 8.49       | 1.96   | 16.34 | sandy loam |
| Rca (23)25-41       | 23.39  | 18.35     | 35.47     | 7.80       | 12.25      | 2.73   | 22.78 | light loam |
| C 41-60             | 27.01  | 19.79     | 31.99     | 7.46       | 11.09      | 2.64   | 21.19 | light loam |

The humus content in the АY horizon is 6.34%, and in humus wedges it reaches 10.9%. Down the profile, its value sharply decreases to 0.8-1.1%. The reaction of the environment fluctuates about the acidic and weakly acidic area. Ca2+ predominates among absorbed cations. In total with Mg2+, they are in the range of 23.3-38.9 mg-eq/100g of soil. The content of available phosphorus corresponds to low and pH values in the upper layer. Potassium reserves are average, increased and even high. They are characterized by high cation exchange capacity and bases saturation.

The gross analysis data indicate the accumulation of CaO, FeO, P2O5 in the surface horizons of the profile and the absence of the process of eluvial-illuvial redistribution of substances, due to the presence of closely lying permafrost.

Soils of the Eravna test site are developed in autonomous conditions and are of semi-hydromorphic. Hydromorphic features in their profile are expressed in increased humus content, powdery carbonates and the presence of signs of gleying in the lower horizons. Hydromorphism of these soils is due to underlying permafrost, which is a source of moisture during thawing and, being waterproof, contributes to the formation of a soil top water. The morphological structure of the profile has the following genetic horizons: AU–AUBI–BI–BCA–Q–CQ. According to the field guide [13], the soil belongs to the type of clay–illuvial quasi-gley frozen chernozem. The texture in the humus horizon is loamy, and it is heavy loamy below (table 1). The bulk density of these soils is low, which is associated with the increased content of organic matter. A gradual increase of bulk density is typical deeper along the profile from 1.15-1.25 г/cm3 in the upper horizons to 1.38-1.55 г/cm3 in the illuvial horizon, and in the lower layers of the soil profile in horizon C it reaches 1.73 г/cm3. The total soil
porosity in the soddy horizon is 67%, in the AU horizon it is 54% and decreases in the underlying ones to 43 and 36%. In the 0-20 cm layer, the values of the total moisture capacity and the lowest moisture capacity are 57 and 25% of the dry soil mass, which is due to the better humus content and structure. In the BI horizon, due to a sharp decrease in the humus content, the value of these hydrological parameters decreases. In the BI horizon, the wilting moisture value is slightly higher than in the AU horizon, which is due to its higher density and illuvial accumulation of finely dispersed particles. The active moisture is the highest in the AU and BI horizons (16-22 mm), while in the BCA horizon it decreases to 10 mm. The water regime of these soils refers to the periodically flushing permafrost type.

The reaction of pH is neutral in the upper horizons, while in the lower horizons it is slightly alkaline. The humus content is 11.4% in the soddy horizon, the humus horizon contains 8.5% and gradually decreases down the profile and in the BI horizon it is 1.3%. The amount of absorbed bases is high and amounts to 32-43.5 mg·eq/100g of soil with a clear predominance of Ca cation.

Gross analysis data show biogenic accumulation of CaO, Na₂O, K₂O, P₂O₅ in the surface horizons to 60 cm depth. There is an increased content of calcium in the carbonate horizon. Due to the heavy particle size distribution, high humus content of the upper horizons and carbonate content of the middle horizons, the soils have a high loss on ignition.

The soils of the Khurumsha test site are formed under steppe vegetation on shallow crystalline rocks. The described soils have a morphological structure of the profile (O–AK–Rca–R) and belong to the cryo-humus lithozems type. The particle size distribution is sandy loam (table 1). The pH of the medium is slightly alkaline. The cation exchange capacity is 21.25 mg·eq/100 g, the amount of absorbed bases is high.

In Russia, systematic measurements of the temperature profile of soils are performed manually [17]. Measurements from 0 to 0.20 m are only carried out in summer, and measurements from 0.20 to 3.20 m are performed daily year-round, including in winter. The established ASMC network [18] allows information to be promptly received on the indicators of the atmospheric and soil climate and at regular intervals [19]. Soil temperatures at Toolik Station, Alaska, are represented only by daily average values along the profile from the soil surface to a depth of 1 m. Measurements are made with a Campbell 107 and MRC Temperature Probe. In such systems, each sensor has a cable. These cables are usually bundled, and each cable is a heat conductor. This heat adds an error to the measurement due to the thermal influence of the cables on each other [20]. Therefore, the ASMC temperature probe is free from these disadvantages. The probe is made in the form of a three-wire printed circuit board with high-precision digital thermometers soldered to it, protected by a heat-shrink tube. Thanks to the calibration in the range of −55… +50°C, the accuracy of the sensors is brought to ±0.1°C [7].

Figure 2. Temperature regimes of the soils freezing and thawing processes:

a – soddy–cryo–metamorphic gley permafrost; b – clay–illuvial chernozems of quasi–gley permafrost; c – cryo–humus lithozems, — frozen layer, — seasonally thawed layer.
The data analysis obtained at the test sites shows the spatio-temporal variability of soil temperature from the surface to 3.2 m depth (figure 2). The temperature regime of the soddy–cryo–metamorphic gley permafrost and permafrost chernozems of the clay–illuvial quasi-gley of the Vitim plateau are of the permafrost type, and in the cryo–humus lithozems of the Khurumsha test site – of the long-term-seasonally freezing type. The results of soils thawing and freezing are given on the example of the ASMC test sites.

The amount of days for freezing of soddy–cryometamorphic gley soils along the entire profile in Bagdarin averaged 24 days with a freezing rate of 10.5 cm/day, which is 39 and 117 days shorter than in Yeravna and Khurumsha the speed of which was 5.6 cm/day and 1.4 cm/day, respectively (table 2).

| Parameters | Freezing 2014 | Thawing 2015 | Freezing 2015 | Thawing 2016 | Freezing 2016 | Thawing 2017 | Freezing 2017 | Thawing 2018 |
|------------|---------------|--------------|---------------|--------------|---------------|--------------|---------------|--------------|
| **The Bagdarin test site** | | | | | | | | |
| Start | Oct 1 | Apr 22 | Oct 16 | Apr 27 | Oct 2 | Apr 18 | Oct 1 | Apr 21 |
| Completion | Oct 31 | Aug 13 | Nov 2 | Aug 2 | Oct 26 | Jul 29 | Oct 24 | Aug 28 |
| $T$ (d) | 33 | 113 | 17 | 97 | 24 | 102 | 23 | 98 |
| $V$ (cm/d) | 7.3 | 1.4 | 14.1 | 1.6 | 10.0 | 1.6 | 10.4 | 1.6 |
| **The Yeravna test site** | | | | | | | | |
| Start | Oct 12 | Apr 19 | Oct 26 | Apr 22 | Oct 2 | Mar 27 | n/d | n/d |
| Completion | Nov 26 | Aug 25 | n/d | Aug 9 | Dec 1 | Jun 6 | – | – |
| $T$ (d) | 45 | 128 | – | 109 | 60 | 72 | – | – |
| $V$ (cm/d) | 7.1 | 1.9 | – | 2.2 | 4.0 | 1.5 | – | – |
| **The Khurumsha test site** | | | | | | | | |
| Start | n/d | n/d | n/d | n/d | Oct 16 | Mar 31 | Oct 10 | Apr 8 |
| Completion | – | – | – | – | Mar 8 | May 15 | Feb 28 | Apr 24 |
| $T$ (d) | – | – | – | – | 143 | 46 | 140 | 16 |
| $V$ (cm/d) | – | – | – | – | 1.5 | 3.9 | 1.3 | 10.0 |

At the southern test site ‘Khurumsha’, the thawing process along the entire profile is faster and lasts an average of 31 days at 6.9 cm/day speed. It is 71 and 87 days shorter than at the Bagdarin and Yeravna test sites, and the thawing rate of which is 1.6 cm/day and 2.0 cm/day respectively.

At the northern test site ‘Bagdarin’, the freezing process of the permafrost soils begins in late September – early October in the central part of the Vitim plateau, which is 11 days earlier than in the soils of the Khurumsha test site, respectively. In permafrost types freezing ends with merging at the end of October and at the beginning of November with continuous permafrost at 2.0 m depth in Bagdarin.

The thawing process of permafrost soddy–cryometamorphic soils of the Bagdarin test site begins in late April. The onset of freezing usually coincides with the first frost in October. This is how the full cycle of freezing and thawing of permafrost soddy–cryometamorphic soils ends.

The thawing process along the entire profile is faster in the cryo–humus lithozems of the Khurumsha test site and lasts 16 days at a thawing rate of 10.0 cm/day. It is 82 days less than the thawing rate at the Bagdarin test site, which is 1.6 cm/day. Long-term-seasonally freezing soil types were frozen only for 5.5-6 months during the observation period, remaining thawed in the base of the rock for most of the year, whereas in permafrost soils, the picture is fundamentally different.
Here, permafrost soils only thaw in summer seasonally for 4.5-5 months, remaining frozen in the soil-forming rocks for most of the annual cycle.

The penetration of positive temperatures and its duration at different depths is of great interest in the studied soils. The collection, systematization and analysis of these data show a great heterogeneity of the soils temperature and permafrost regime.

Regularities of penetration and distribution of positive temperatures are more than 0°C at 100 cm depth. On the steppe sandy loam cold soils of the Selenginsky middle mountain, the thawing process begins already in late March – early April, that in 10-20 days earlier than in soils of the Vitim plateau. So, in cryo–humus lithozems of the Selenginsky middle mountain, this indicator is 220 days, in 94 days more than the positive temperature duration at 100 cm depth in the soils of the Bagdarin test site.

The greatest differences were found in the duration of temperatures above 5°C at 100 cm depth. Thus, in the cryo–humus lithozems of the Selenginsky middle mountains, this indicator averages 178 days, which is 135 and 88 days higher than the temperature duration in the soils of the Bagdarin and Yeravna test sites, respectively.

The greatest differences were found in the duration of temperatures above 5°C at 100 cm depth. Thus, in the cryo–humus lithozems averages 145 days at 20 cm depth, which is 69, 45 and 53 days more than in the Bagdarin and Yeravna test sites, respectively. Temperature above 10°C does not reach 100 cm depth on permafrost soil types, except for the Khurumsha test site.

4. Conclusions
New ASMC has been used for a comparative assessment of the temperature and permafrost soils regimes, which allows receive on-line information about the atmospheric and soil climate parameters throughout the year and with a given frequency.

It is established that the processes of thawing and freezing primarily depend on the solar radiation and the amount of precipitation. The further distribution of temperatures in the soil is associated with the soil cover and soil properties (texture, structure and density, humus content, moisture availability).

During the observation period in seasonally-freezing types of soils, negative temperatures are observed for 5.5-6 months, the soil profile remains thawed at the depth 2.2+ m for most of the year. Permafrost soil types thaw seasonally only in summer for 4.5-5 months, remaining permanently frozen at the depth from 2.0 m in ‘Bagdarin’ and 3.2 m in ‘Yeravna’.

The following annual indicators are informative for the soils of the region: temperature above 5°C penetration at 100 cm depth and the amount of days with temperature above 0.5°C and 10°C at 20 cm, 50 cm, and 100 cm depths.

Thus, freezing rate and period with negative temperatures are higher in forest–meadow and meadow–steppe sandy–loamy permafrost soils of the Vitim plateau. These processes are related to early cold, as well as high soil humidity and close to the surface of the permafrost table.

Acknowledgments:
The research was carried out within the framework of the budget projects (121030100228-4 and 0270-2021-0004); partly with the financial support of the Russian Foundation for Basic Research in the framework of the scientific projects: No. 18-45-030033 “Quantitative study of the dynamics of soil climate change on the southern border of the permafrost area under the influence of the global warming process in Western Transbaikalia”, No. 19-29-05250 “Temperature field of soils in the permafrost zone of Transbaikalia: development regularities and changes forecast”.

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