Response of middle-taiga permafrost landscapes of Central Siberia to global warming in the late 20th and early 21st centuries

Alexey A Medvedkov

Department of World Physical Geography and Geocology, Faculty of Geography, Lomonosov Moscow State University, Leninskiye Gory, 1, Moscow 119991, Russia,

Email: a-medvedkov@bk.ru

Abstract. In this paper, regional features of a climatogenic response of the middle-taiga permafrost landscapes of Central Siberia, as well as corresponding transformations of the exodynamic processes, are considered. Lithological-geomorphologic and landscape-geocryological data are analyzed with large amounts of actual data and results of monitoring surveys. Specific features of an ecotone localization of middle-taiga permafrost landscapes and their typical physiognomic characteristics are described. A comprehensive investigation of representative key sites makes it possible to discover the response of different types of permafrost landscapes to regional climate warming. A rapid increase in the active layer depth, slower creep, transformations of the moving kurums, intensive solifluction, and a local replacement of solifluction by landslides-earthflows are revealed within ecotone landscapes of the cryolithozone.

1. Introduction
The periphery of the permafrost zone in the Eurasian North is a planetary ecotone with patchy landscapes, especially in areas with complex geological and geomorphic structure. The study focuses on the Central Siberian segment of the area embracing the left- and right-bank areas of Yenisei, as well as the lower reaches of the Podkamennaya Tunguska River.

A vivid example of diversity of the ecotones landscape is the western part of the Middle-Siberian High Plateau, in the lower reaches of the Podkamennaya Tunguska River. It is important to know how permafrost conditions and landscapes will change in the given part of the ecotone in connection with the global warming. To answer this question, it is necessary to 1) identify permafrost and non-permafrost landscapes and 2) understand whether the stability of permafrost varies with the landscape features. The outcome of this research will provide a basis for developing a scenario for the evolution of morphogenetic systems and landscapes in the ecotone area under study in relation to global warming.

In the monograph of Gorshkov et al. [1] significant amount of geohistorical, paleo-permafrost, geomorphological, and landscape data on this region and research topic was analyzed. According to the results the authors note that solifluction is a very important attribute of the whole system of cryogenic exodynamic processes that worked in unstable conditions during interglacial Pleistocene periods. It is confirmed by the data of stratigraphic location of fossil permafrost traces in the section of Late Pleistocene deposits of the old periglacial zone of the Yenisei Siberia. Sudden climate warming at the beginning of each interglacial period pressed the permafrost deeper, as it also occurs nowadays, and activated the solifluction process. After analyzing numerous monitoring data of the cryolithozone, Konischev [2] notes that immediate response of permafrost to warming climate occurs in autonomous ecosystems (or those close to them). In the study area we observed similar regularities, but with a much more complicated response [3].

The international program of circumpolar monitoring of active layer (CALM) and the international project on the thermal state of permafrost (TSP) are running for more than 15 years. However, Central Siberia is still not covered by geocryological research within the framework of these programs. Therefore, our ongoing landscape-geocryological investigations at representative sites are of special importance. We
conducted more than 1000 field observations and measurements. As a result of these observations, we recorded the analyzed changes and their indicators shown in this paper.

2. Materials and methods

The field studies (2007–2016) included a landscape–geoenvironmental inventory of natural components at transects through the main types of forest, swamp, and burnt catenas in the left- and right-bank parts of the Yenisei Siberia, boreal taiga subzone (Figure 1). The route profiling was carried out along transects across and along the geomorphological catena, taking into account conjugated relief surfaces, most diverse in morpholithogenic, soil–geographic, and landscape respects. Detailed landscape descriptions along the route were accompanied by the determination of the upper boundary of permafrost with the use of a probe; diagnostics of permafrost and nonpermafrost processes was carried out.

Figure 1. Map of key study areas in Yenisei Siberia.

In the course of route surveys special attention was given to field studies of the landscape structure of key areas, taking into account the specifics of surface deposits and the character of their geomorphological differentiation; landscape indication of permafrost natural–territorial complexes, and ranking landscape complexes into permafrost and nonpermafrost. A comprehensive analysis of this data made it possible to identify and outline (at the level of complex stows) landscape complexes most vulnerable to various external impacts (including climatic ones). In addition, the field studies included monitoring of different types of permafrost and nonpermafrost stows in terms of the specifics of their response to climate warming, which were compared with the data obtained in the course of field studies in the 1970s, 1980s, 1990s, and 2000s.

Special attention was given to observations of specific informative natural objects and phenomena. — Stone streams. In the zones of occurrence of active stone streams, the specifics of local overgrowing by moss–lichen cover were studied, and a number of unstable boulders was determined. For low-activity, closed stone streams, the degree and character of forestation and the specifics of stand timber, in particular, the share of inclined trees, were determined. Succession changes in the taiga vegetation within the relatively stable covers and stone-stream–deflection (block structures with loam colmatage) were examined;
— *Soliflual deposits*. Signs of weakening or degeneration of solifluction were assessed, including the presence of inclined trees with vertical tops, as well as the overgrowth of solifluction hollows—disruptions in the above-soil cover. Cases of replacement of solifluction slopes and glacises* on river banks by local landslides—creeps because of a recession of permafrost roof and an increase in the instability of bank massifs were detected;

— *Relic permafrost relief forms*. The cryogenic morphosculpture of the Upper Pleistocene forms of solifluction origin, the signs of thermokarst, and the features of their landscape occurrence were analyzed. Analogous modern formations were sought for and studied;

— *Undergrowth of parvifoliate species (birch, aspen)*. The causes of explosive rise of the undergrowth of parvifoliate species in dark and light coniferous forests were studied and analyzed, in particular, in the habitats that had not been typical of such before.

3. Results and discussions

3.1. Climate changes

Climate warming in the Central Siberian region has been recorded for more than 30 years since the early 1980s (Figure 2). Here, the mean annual temperature increased by 1–2°C and more as compared with the previous, colder period from the late 1940s to the late 1970s. Since the early 1980s, the winter became warmer, and the spring and autumn, longer.

Years with shorter summer also occurred. In the cold 1974, the minimal mean monthly air temperature in January at Bor Settlement was found to be −35.1°C, while that in the warm 1995 was −17.8°C. At the same time, the difference between the mean July temperatures in the same years did not exceed 1.7°C. The increase in the mean annual temperature in warm years is due to both the higher temperatures in the cold season and the longer warm season.

![Figure 2](image.png)

**Figure 2.** Variations of mean annual air temperature for 1900–2012 according to data of hydrometeorological stations of Krasnoyarsk krai in Turukhansk V., Bor Settl., Kuz'movka V., and Yeniseisk T.

Analysis of Figure 3 suggests that the amplitude of variations of winter temperatures is much larger than those in other seasons, a feature that determines their leading role in the annual temperature. It can be clearly seen that the last 20 years of the 20th century can be distinguished by their winter maximums. Note that a concentration of high winter temperatures falls into the period from the late 1980s to the mid-1990s.

![Figure 3](image.png)

**Figure 3.** Distribution of mean air temperature over seasons based on data of ZGMOS in Bor Settl. (Turukhansk district, Krasnoyarsk krai) for 1900–2009.

3.2. Characteristic features of permafrost landscapes and their tolerance to climate warming

The permafrost landscapes are very sensitive to climate warming, though to a different degree. Of importance in this situation are their indication and the identification of occurrence specifics. Permafrost
processes in boreal landscapes often manifest themselves under favorable substrate conditions, irrespective of the heat supply to relief elements. Thus, the lithological–geomorphological and landscape–geographic analyses showed that permafrost stows in the lower reaches of the Podkamennaya Tunguska occur in the surface deposits of aleurite–pelite composition [4]. This demonstrates the priority role of the lithological factor. Therefore, the southern boundary of Upper Pleistocene glacial and lacustrine–glacial deposits (with predominant aleurites and clays containing inclusions of sand, gravel, and sporadic boulders) which cross the area under study is an important landscape boundary too. Previously, landscapes in the lower reaches of the Podkamennaya Tunguska were studied to verify and adjust geological mapping results [5]. The first attempt to differentiate between permafrost and non-permafrost landscapes was made by Gorshkov, Karrasch, Paramonov [4], and Fedorov [6].

In genetically different surface deposits there are significant varieties in seasonal thaw depth. Estimated seasonal thawing of peat soils occurs to a depth of 0.3–0.5 m, silts and clays thaw to depths between 0.8–1.0 m in shadowy and cold conditions, and to 2.0 and even 2.5 m where the ground gets more heat in summer. Coarse grained sand and pebble rock thaw to a depth of 3–4 m. Permafrost varies in thickness from several meters to 25–30 m [7].

Our studies show that permafrost rocks manifest themselves in different stows, which feature dystrophy, suppression, and species poverty, appreciable disturbances of the daily surface, specific soil profile with gley signs, higher watering of soils and surface deposits, and manifestation of cryogenic processes and phenomena.

Thus, the key characteristics of permafrost landscapes are:
- the character of vegetation cover: suppressed thin taiga with appreciable tilt of trees, sparse stands and dwarf birch thickets, moss–brush vegetation with the predominance of sphagnum mosses (Sphagnopsida);
- specific soils: cryogenic peat–gley, alluvial–swamp with signs of gley and cryogenic skeletal (stone-stream soils);
- relief microforms: solifluction windows–breaks (holes–breaks) (Figure 4), solifluction ledges, frost mounds, thermokarst subsidence;
- relief mesoforms and their outlines: solifluction swells (foot plumes); watered and low-mobility stone-streems: hanging bogs; ditch-type channels of creeks and rivers with land-slide signs;
- the state of surface deposits: viscous–flow consistency of disperse soils; active and watered stone streams (individual boulders are unstable);
- the composition of surface deposits: moraine clays, loams, lacustrine–glacial and alluvial clays, aleurites, frozen peat, solifluction disperse deposits, highly watered boulders of stone-stream fields;
- higher watering of a stow due to groundwater outcrops.

Figure 4. Solifluction hole–break in ground vegetation filled with cold water on the glacis–floodplain (1–2 m in diameter and 0.5–0.6 m deep in the peat-and-plant layer, usually found every 80–100 m). Water is a sign of the presence of a permafrost aquiclude near the daily surface. (Photo by the author).
Nonpermafrost landscapes show
- the presence of full-scale erect tree vegetation;
- high occurrence of hard rocks under a thin mantle of surface deposits;
- relatively good drainage.

3.3. Sustainability of landscapes to the climate warming
As to the stability of permafrost landscapes, some differentiation of occurrence toward the south was found. If some type of permafrost stows occurs furthest to the south, then, other conditions being the same, it can be regarded as the most tolerant to climate warming [8]. In this context, three types of stows can be identified in the region under study by their tolerance to climate warming (Table 1):

- low-stability stows of glaciers with good water supply and slopes with open stone flows and summit plains (at the end of the summers of 2006-2007 the active layer thickness was no more than 1.2–1.5 m in the mentioned landscapes. However, during the same period of 2016 it was about 1.6–1.9 m and sometimes 1.9 m and deep);
- stable stows of slopes, glacis, and glacis-floodplains** (Under the forest vegetation within these stows we registered a permafrost table at a depth of 0.5–0.8 m. We suppose that in these stows the active layer thickness increased not more than by 0.2–0.3 m during the last 9 years. More pronounced changes occurred in areas located near thermokarst ponds and where forests or dense bush groves are absent);
- highly stable-polyfactor permafrost stows on slopes with poor heat supply: "hanging" bogs*** of heat-deficient slopes (the location of a permafrost table is approximately at the former level: about 0.4–0.5 m under holes and 0.7–0.8 m under hummocks) and forested floodplains of large rivers (in these stows the permafrost table depth is about 0.2–0.3 m under holes and reaches 0.4–0.5 m under hummocks).

Thus, the most stable permafrost stows are hanging bogs of cold slopes and forested floodplains of major rivers (Table 1).

Table 1. Dynamics of the top of permafrost in different types of landscapes.

| Types of permafrost landscapes | Depth of the top of permafrost in 2007 | Depth of the top of permafrost in 2016 |
|--------------------------------|----------------------------------------|----------------------------------------|
| well heat provided summit plains | 1.2–1.5 m                              | 1.6–1.9 m                              |
| heat-deficient slopes, glacises | 0.5–0.8 m                              | 0.7–1.0 m                              |
| "hanging" bogs                  | 0.4–0.7 m                              | 0.4–0.7 m                              |
| forested floodplains of large rivers | 0.3–0.4 m                          | 0.3–0.4 m                              |

* Glacises are accumulative surfaces with slopes from a few degrees to a few tens of minutes, constituted by decession, solifluction and deluvium, forming foot plumes or occupying valley beds.
** Glacis-floodplain includes areas of glaciers near the river bed, which are inundated during spring flood, under meadow-bog or draft birch vegetation on alluvial-gley and peaty-permafrost soils
*** "Hanging" bogs ("hanging" peat) are mostly located on steep near-river slopes with low heat supply.

A stone flow underlies a thin peat layer in each of such bogs. The permafrost peatery shows high segregation ice content. The most impressive are ice inclusions with a size of a walnut. The permafrost layer is overlain by ground vegetation, consisting of mosses, lichens, and dwarf shrubs with the abundance of ledum and dwarf arctic birch. However, under the conditions of global warming, the permafrost in the area can aggradate because of the longer vegetation period, resulting in a thicker peat–vegetation layer, which serves as a heat insulator.

3.4. Climate-driven response of the most vulnerable permafrost landscapes
In the lower reaches of the Podkamennaya Tunguska, the least stable permafrost is confined to the landscapes of low (200–250 m) summit plains and gentle slopes, composed of clays, loams with inclusions of individual boulders, and aleurolites-fine-sand deposits of glacial complex. Common in such places are bog complexes with low thin (crown density of 40–50%) cedar–fir taiga with birches and larches on a peaty–gley cryogenic soil with a most–brush and, sometimes, lichen ground cover.
At the depth of zero annual temperature variations, the cryogenic soil is cooled to 1°C and even to fractions of degree below zero. The active layer in loams and clays is the layer of seasonal freezing and thawing, which is 0.8–1.0 m in thickness [7], [9]. Since the mid-1990s until now, the top of high-temperature (-0.1 – -1.0°C) permafrost shifted 1.5–2 m and more down, demonstrating the process of permafrost degradation because of the warming of its strata.

The beginning of permafrost degradation had an immediate effect on the appearance of permafrost landscapes, i.e., the disappearance of water in solifluction holes-breaks; fallen trees can be seen with the entire spreading-root assemblage torn out of the earth, because they fall more easily under wind impact, and their root base lost the support of the solid frozen substrate. The result was an increase in the occurrence of relief forms of biogenic origin (the so-called iskors) in the landscapes of the insular-permafrost subzone. Local replacement of solifluction by landslide processes was observed in the zones of river erosion intensification. Because of draining, some plants, primarily horsetail, lose their green color, making the ground vegetation cover yellowish–golden. Small thaw lakes with collapsed and dead forest stand appeared.

In the basements of stone streams and detritus, called kurums, the permafrost retreats downward faster than in the areas of permafrost thin forest. Studies in the key areas show that bald-peak ice melted, small depressions formed, and cold subsurface creeks disappeared in the kurums, primarily on slopes with southern and western aspects. The kurums overgrow with lichens, dwarf shrubs, and individual trees (Figure 5). In the low reaches of the Podkamennaya Tunguska River, the kurums not covered by forest, even on slopes with poor heat supply, on valley beds, on slopes and summit plains with elevations not exceeding 400 m have lost their bald-peak ice. Warm kurums are common in the northern part of the Yenisei Range and the western part of the Central Siberian Plateau up to the Nizhnyaya Tunguska River in the zone of Severnyi kamen’ trappean massif, which is as close as 70 km south of the polar circle. The permafrost on the beds of deep valleys and on steep slopes of northern and eastern aspects with low heat supply is more tolerant to warming. The permafrost roof is still stable on the upper plateau of the western Central Siberia with absolute elevations of 550–700 m.

An analysis of the collected material allows us to suggest that a protection response in the form of negative feedbacks forms in the kurums of the boreal taiga subzone. At the first stage, bald-peak ice melts and kurums overgrow with mosses, lichens, and tree species. At gradual overgrowth of a kurum, fine soil accumulates, filling gaps between boulders and forming a more impressive soil profile A1–AB–C of brown taiga skeletal soil [3], [8]. The accumulation of fine earth and the rate of kurum overgrowth were found to increase in the zones of concentration of black crustose lichens. At further accumulation of fine earth, the brown taiga skeletal soil transforms into a peaty brown taiga soil, the share of disperse deposits and the thickness of peat–vegetation layer increase, and the watering of kurum and its isolation from the lower air layer grow. The formation of hanging peat bogs at the second stage is accompanied by aggradation of permafrost because of a growth of icy rocks.

**Figure 5.** A kurum overgrown by lichen and young birches on the right bank in the middle reaches of Bol’shaya Chernaya river. The abundant growth of moss and underbrush vegetation on the kurums leads to the formation of peaty soil layers on slopes which are frozen at depths of 0.3–0.5 m. (The left tributary of Podkamennaya Tunguska river). (Photo by the author).
Our studies show that in 1998–2016 in Central Siberia only high-temperature permafrost experienced degradation: kurums in all subzones of the permafrost zone, though not including the upper peneplain, and the high-temperature permafrost in pelite rocks, only in insular-permafrost zone and further southward [3].

4. Conclusions
A large body of data was obtained suggesting the beginning of permafrost degradation in the middle boreal subzone in the Yenisei basin (not less than 70% of the area it occupies within the ecotone).

Figure 6. Solifluction landslide in the middle reaches of the Coligny river (right tributary of the Podkamennaya Tunguska river). Landslides - slides are typical for slopes of about 10 to 30 degrees. Such sites have a significant increase in the active layer capacity. (Photo by the author)

The most significant processes of response to climate warming in the boreal landscapes of the Middle Yenisei area include an increase in the thickness of the active permafrost layer and intensification of solifluction (Figure 6);
- cases of local replacement of solifluction by land-slide motion of soils in the zones of active river erosion;
- anomalously frequent falls of trees that have spreading-type root systems in areas where clay soils are waterlogged, have viscoplastic consistency, and are 1.5 or more meters in thickness;
- better drainage on summit plains and adjacent gentle slopes;
- higher mobility of large boulders on kurums because of bald-peak ice melting, as well as the number and area of overgrowth spots of mosses and lichens;
- depletion of subsurface streams under the kurum boulder cover;
- intensification of thermokarst processes within swampy areas.

The ecotone under consideration is located in the western part of the Central Siberian Plateau and the eastern margin of the West Siberian Plain. The response to climate warming causes changes in the permafrost-landscape conditions, exodynamic processes, and the production of natural systems, and affects the life support of the local population [10]. The understanding of the processes taking place in a permafrost ecotone is of importance for assessing the changes in modern boreal landscapes in the Northern Eurasia and the state of its natural-environmental resources in the future.

Acknowledgements
The study was supported by the Russian Foundation for Basic Research (project 16-35-00327- mol_a) and the Council for Grants of the RF President (project MK - 7614.2015.5)
References

[1] Gorshkov S P, Vadenberghe J, Alexeev B A et al 2003 Climate, Permafrost and Landscapes in the Middle-Yenisei Region (Moscow: Moscow State University Press) p 96

[2] Konishchev V N 2009 Response of permafrost to the climate warming Vestn. Mosc. St. Univer. Geogr. 4 10-20

[3] Medvedkov A A 2016 Mid-Taiga Geosystems of the Yenisei Siberia under climate change (Moscow: MAKS Press) p 144

[4] Gorshkov S P, Karrasch H, Paramonov A V 1998 Geomorphologic Indication of Permafrost and Non-Permafrost Landscapes in the middle taiga of Central Siberia Geomorph. 4 55-60

[5] Astakhov V I, Gerasimov L M, Eromenko V Y et al 1978 Complex of Remote-Sensing Methods Used in Geological Mapping of Taiga Areas (Leningrad: Nedra) p 247

[6] Fedorov A N 1991 Permafrost landscape of Yakutia. Methods of Indication and Problems of Mapping (Yakutsk: MPI SB RAS) p 140

[7] Leshchikov F N, Shats M M 1983 Permafrost in the Southern Central Siberia (Novosibirsk: Nauka Press) p 169

[8] Medvedkov A A 2015 Geoenvironmental response of the Yenisei Siberia mid taiga landscapes to global warming during late XX–early XXI centuries Water Res. 42 (7) 922-931

[9] Gorshkov S P 2008 Environmental shock in the Central Siberia: causes and consequences Geogr. Perv. Sent. 4 10-16

[10] Medvedkov A A 2013 The Kets ethnos and its "feeding landscape": ecological-geographical and socio-ecological problems under globalization and changing climate Geogr., Envir., Sust. 6 (3) 108-118