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GEOCRYOLOGICAL MONITORING AND PREDICTION

BACKGROUND GEOCRYOLOGICAL MONITORING IN NORTHERN TRANSBAIKALIA REGION

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The observation results for the Chara River Basin and its mountain frame (Northern Transbaikalia) are summarized and analyzed. A suggestion is made to develop the natural-dynamics ("background") permafrost monitoring, which includes long-term automated measurements of ground temperature and water content, as well as hand-operated active layer depth measurements. The main principles of the background monitoring and the possible ways of interaction with other types of environmental observations are described.

Geocryological monitoring, temperature measurements, permafrost dynamics, climate change

INTRODUCTION

Geocryological monitoring (GM) plays an important role in the study of the natural and technological systems of the permafrost zone and in ensuring their normal function. In practice, regular geocryological observations are made mainly at large industrial and infrastructural facilities (railways, trunk pipelines, deposits of natural resources, urban territories). Observations have to be conducted in the impact zone of engineering facilities, which makes evaluation of the role of climatic factors in the dynamic of geocryological conditions more difficult.

In this regard, the issue of background geocryological monitoring (BGM) comes to the fore. The main task of BGM is to evaluate the current state and dynamics of geocryological conditions in undisturbed landscapes [*Zheleznyak, 2005; Pavlov, 2008; Melnikov, 2012*]. In Russia, BGM is conducted by the Melnikov Permafrost Institute, SB RAS, Institute of the Earth Cryosphere, SB RAS, and other organizations. These works are united by the project GTN-P, supervised by the International Permafrost Association. The observations conducted under the international programs CALM, TSP and GTN-P indicate the ambiguous response of the permafrost conditions to changes in the environment [*Romanovsky et al., 2003, 2008; Tarnocai et al., 2004; Pavlov, 2008; Drozdov et al., 2012; Guglielmin and Cannone, 2012; Leibman et al., 2012; Ponomareva et al., 2012; Sharkhuu and Sharkhuu, 2012*].

In interpreting the monitoring results, there arises a problem of evaluating the role of regional and local changes in the heat exchange conditions (ground water dynamics, redistribution of the snow cover, temporary inundations of land, vegetation disturbances due to fires or territorial development).

The question remains insufficiently investigated as to what degree the history of permsafrost development affects their present dynamics. The past epochs of cooling and warming may exert significant influence on the modern temperature of rocks [*Kudryavtsev, 1983*].

OBJECTS AND METHODS OF BACKGROUND GEOCRYOLOGICAL MONITORING

The objects of BGM are permafrost (as a geological body) and the character of changes in the rocks, in particular, the temperature, moisture content, ice content, etc. BGM is based on landscape zoning, which is complemented by description of the structure of inhomogenuities of geocryological conditions within uniform landscape units ("territorial types").

Preparation for the monitoring starts with supervision of the available data relating to the temperature dynamics and the properties of permafrost, which is complemented by analysis of the specifics of heat exchange between rocks and the atmosphere in the indicated micro zones. In the process of BGM, indicators are recorded determining the current state and dynamics of sediments. The temperature of rocks is measured near the day surface (normally at the depths of 1 cm or less); in the lowest part of the seasonal thawed layer (ATL); in the upper part (near the top) of the permafrost; at the base of the annual fluctuations layer. Temperature sensors are placed in the wall of a prospecting hole, which is filled after boring, considering the ground cross section. Sensors are placed in the permafrost in thermometric boreholes with the diameter of 100 mm or less and 30 m or less deep.

In addition, properties of rocks are investigated (the moisture content, the ice content, salinity, etc.), affecting the characteristics of the heat exchange processes. Observations over the thickness of the seasonal thawed layer are especially important. Where possible, they are combined with micro meteorological, geobotanical, and geothermal measurements.

An important role in the solution of the BGM issues is played by the investigation of external influence on the temperature behavior of rocks (the air temperature, specific features of the distribution of the snow and vegetative cover, the character of the surface watercourses, etc.). In the mountains, these factors are related to the phenomenon of the altitudinal belt [*Romanovskiy et al., 1991*]. The total heat flow from the active layer is a significant characteristic reflecting the conditions of the temperature dynamics in the uppermost horizons of the permafrost. This heat flow depends on the character of the ground cover, the regime of surface moistening and the processes of heat and mass exchange in the active cover, i.e., on the conditions which may change fast and irregularly. As a result, great difference between the mean annual rock temperatures is often observed, which reaches 9 °C at the base of the seasonal fluctuations layer. The areas of contrast and fast-changing geocryological conditions should be used for arranging sites for *monitoring of geocryological processes*, such as thermokarst, heaving, aufeis, etc.

THE CHARA SITE OF BACKGROUND GEOCRYOLOGICAL MONITORING: THE NATURAL CONDITIONS AND THE STUDY

The area of the works is located on Stanovoe highland (Fig. 1) and includes mountain chains and

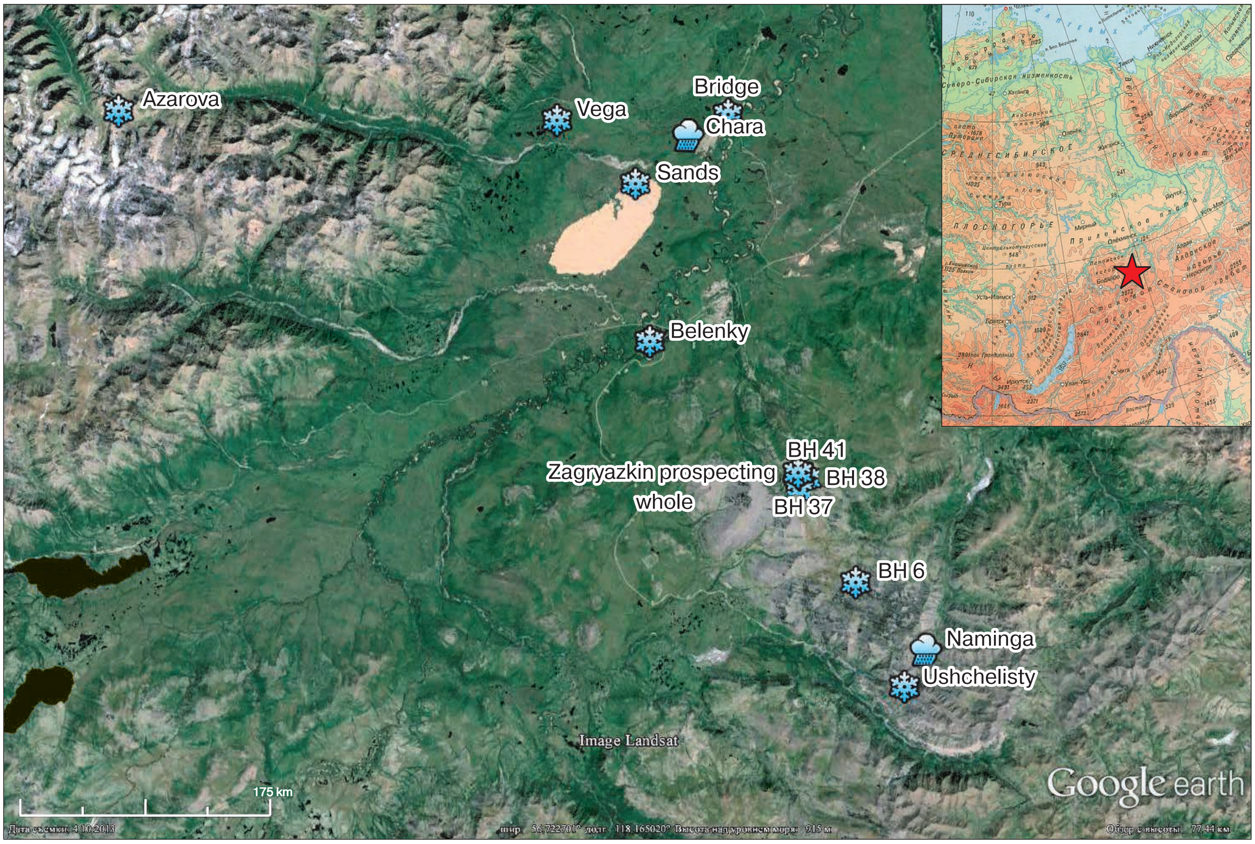

Fig. 1. Sites of background geocryological monitoring of the Sergeev Institute of Environmental Geoscience, Russian Academy of Sciences, in northern Transbaikalia.

intermountain depressions relating to the Baikal rift zone [*Romanovskiy et al., 1989*]. The actual elevations of the observation sites vary from 700 m ("Bridge") to 2,036 m ("Azarova"). The region's climate is sharply continental, with severe long winters and short warm summers. The complicated indented relief of Northern Transbaikalia exerts essential influence on the local climatic conditions. Northern Transbaikalia is a region with highly developing warming of the climate [*Pavlov, 2008*]. The microclimatic variations of the mean annual temperatures do not exceed 4 °C and are associated with a high altitudinal belt [*Karausheva, 1977; Romanovskiy et al., 1991*]. The mean annual air temperature increases as the true altitude rises to 1,100–1,200 m and begins to go down above this figure.

According to the data provided by the state meteorological station in Chara, the average temperature rising rate has been close to 0.03 °C/year over the recent 50 years (Fig. 2), with certain acceleration of the temperature rising rate and the range of the positive anomalies observed over the recent years [*Perlstein et al., 2012*].

In the vegetation of the Chara hollow, East-Siberian middle taiga deciduous mountain forests prevail [*Sochava, 1954*]. At the foothills of the Udokan Ridge, open and light deciduous forests occupy large territories [*Medvedev, 1979*]. The ground cover in the territory in question is mainly represented by combinations of moss and grass of the pyrogenic transformation series. Over the vast areas of the anthropogenic disturbance, the primary vegetation is not recovered; instead, new plant communities emerge there, more suitable for the modern climatic conditions.

Since 2005, one of the BGM sites located near the village of Chary, Kalar region, Zabaikalsky krai, has been the working place of the geocryological laboratory of the Sergeev Institute of Environmental Geoscience (Fig. 1). Here observations were conducted in the 1960s and 1980s of the 20th century [*Sergeev et al., 2007*]. Regular geothermal observations in Northern Transbaikalia started in the 1960s with the comprehensive works of the Melnikov Permafrost Institute [*Klimovskiy, 1966; Nekrasov and Shastkevich, 1966; Shastkevich, 1966*]. It has now been ascertained that permafrost is continuous in the mountains and discontinuous in the Chara hollow. Permafrost thickness reaches 900 m in the highlands and 450 m in the Chara hollow [*Zheleznyak, 2005*]. The depth of seasonal thaw varies on average from 0.5 m (in peated areas) to 1.7–2.0 in in boulder streams [*Zabolotnik and Klimovskiy, 1966*] and, possibly, to 5 m of seasonal thawing in the masses of drift sands.

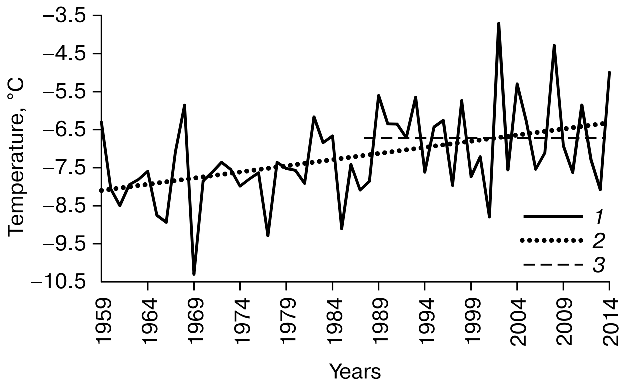

Fig. 2. Mean annual air temperatures at the Chara meteorological station (averaging from September to August):

1 – the temperature course; *2* – the linear trend for the period of 1959–2014; *3* – the linear trend for the period of 1988–2014.

EARTH TEMPERATURE MONITORING

The main result of the Earth temperature monitoring is the series of comparable data on the temperatures of air, ground surface, and rocks in the representative conditions of conditionally undisturbed landscapes of the highlands. The characteristic of the territories of observations is shown in Table 1.

In 2008, the authors resumed the previously interrupted state-sponsored meteorological observations at the Naminga meteorological station. They established that the difference between the mean annual air temperatures recorded in Chara and Naminga meteorological stations is subject to annual variation; however, the tendencies of the climatic variations are the same for all the altitudinal belts of the mountains (Fig. 3).

At the majority of the BGM sites, the maximum and minimum values of the mean annual temperatures of the ground surface demonstrate biannual variation; in different types of territories, the mean annual temperatures of the ground surface may differ by 9 °C, which is approximately twice greater than the spatial variations of the mean annual temperatures of the air (Fig. 3, 4). The tendencies of changes in the "soil climate" may differ in different years for different types of territories (Fig. 4).

The observed difference between the mean annual temperatures of the ground surface and of the base of the seasonal thawing layer (the so-called temperature shift) in the territory in question varies not only by the absolute value but also by the sign (Table 1). The vertical gradient (lapse-rate) of the mean annual temperatures in the active layer varies within a rather wide range from −5.2 to +3.5 °C/m. This is due to the differences in such characteristics as the

Table 1. **Locality types of background geocryological monitoring**

No.	Site name, elevation	Type of locality	Mean temperature for 2006–2014, °C		
			air	ground surface	active layer base
1	"Bridge", 700 m	A swamped tall flooded plain of the Chara River. Vegetation: tussock-sedge vegetation community with larch undergrowth	–6.9	–3.4	–5.0
2	"Belenky", 728 m	The first flooded plain terrace of the Chara River. Vegetation:a secondary community complex of dwarf-birch-dwarf shrub-sedge- moss-bog vegetation with larch undergrowth	–6.6	–2.5	–4.0
3	"Sands", 753 m	A mass of drift sands	–	–1.9 (at the depth of 0.2 m)	0.3 (at the depth of 1.0 m)
4	"Vega-23", 805 m	A wide crest of a moraine line, shallow soil superposes dusty sands and sand clays with pebble, with ice laminations. Vegetation: larch-dwarf-birch-ledum-cowberry-sedge-moss-bog forest	–	–	–
5	"Zagryazkin prospecting hole" (borehole 37), 1155 m	A boulder stream slope of the south-western exposure, covered with scarce larch forest with fragments of cedar elfin forest, In the active layer (up to 2.5 m) density air convection is developed in winter	–5.4	–4.9	–9.4
6	Borehole 38, 1464 m	A boulder stream on a watershed surface. Scarce larch and cedar elfin wood with crustose lichen (60 %)	–7.1	–5.7	–5.3
7	Naminga meteorological station, 1510 m	The upper reaches of the Naminga River, an underlain site composed of large-block moraine deposits with sand filler. Vegetation: dwarf cedar forest and reindeer lichen association	–7.2	–3.2	–
8	"Ushchelisty", 1640 m	A watershed weakly swamped saddle in the upper reaches of the Ushchelisty Creek. Peat bog soil is underlain by sandy clay with repeated-wedge ice. Vegetation: dwarf-birch-blueberry-sedge-moss-bog-lichen association in combination with sedge fragments	–8.6	–4.7	–5.0
9	Borehole 6, 1712 m	A boulder stream on an eastern exposure slope of Udokan Ridge. Crustose lichens and scarce copses of cedar elfin forest. In the active layer, density convection of the air is common	–7.5	–6.7	–4.0
10	Borehole 41, 1338 m	The valley of the Klukvenny Reek, the middle part of the southern exposure slope of the Udokan Ridge. there are boulders and detritus with sand filler on the ground surface. Vegetation: scarce larch forest with cedar elfin forest and cowberry growth	–	1.5	–0.6
11	"Azarova", 2036 m	A ground moraine below the end of Nina Axarova Glacier (Kodar Ridge). Shallow (up to 0.2 m) mountain soil, underlain by gruss sediments with sandy filler. The surface is covered with scarce reindeer lichen and dwarf shrub growth	–	–9.3	–7.3

heat exchange mechanism, the value of the phase changes in the active layer, and the total heat flow from the surface into the ground.

The essential negative shift at the site Zagryazkin prospecting hole is attributed to the winter density convection in the boulder streams. As for the positive shift at the Peski and Azarova sites, it is likely to be related to the low moisture content and the high water permeability of the sediments, the temperature of which significantly drops in winter and which thaw fast and become warm as the summer precipitation infiltrates the soil.

The dynamic of the mean annual temperatures in the lower part of the active layer is close to that in the upper part of permafrost and may be used as one of the basic characteristics of the condition and of the tendency of changing the geocryological conditions. The authors describe this dynamic with the normalized difference of the mean annual temperatures within the depth ranges under study (Fig. 5, 6). The nega-

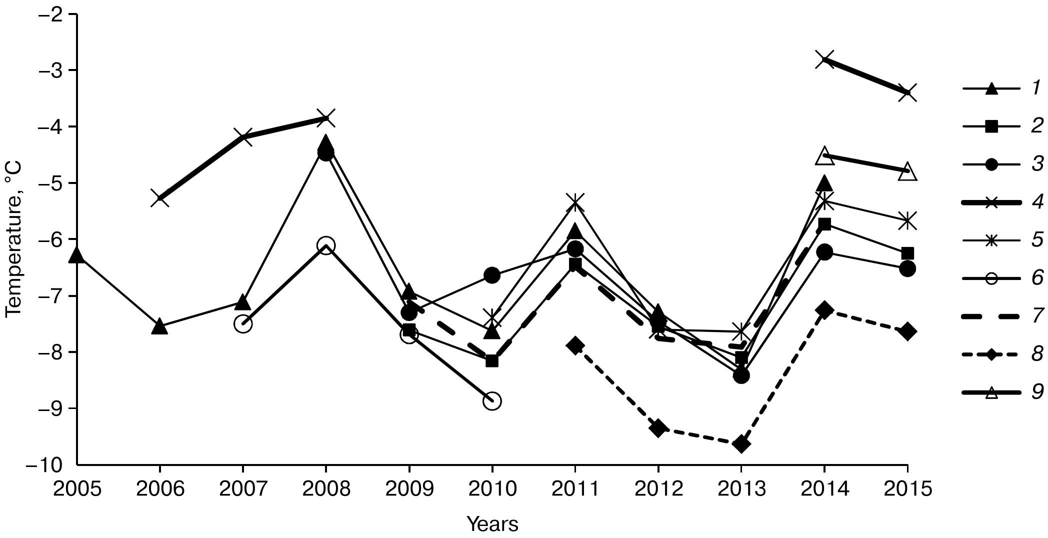

Fig. 3. Mean annual air temperatures at the sites of background geocryological monitoring:

1 – Chara meteorological station; *2* – "Bridge"; *3* – "Belenky"; *4* – "Zagryazkin prospecting hole" (borehole 37); *5* – borehole 38; *6* – borehole 6; *7* – Naminga meteorological station; *8* – "Ushchelisty"; *9* – "Vega-23".

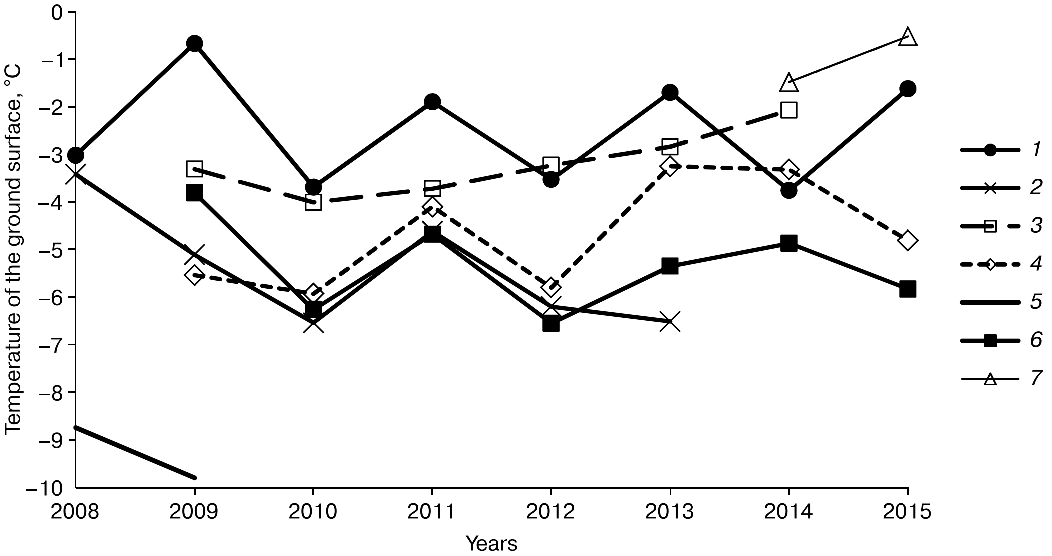

Fig. 4. Mean annual temperatures of the soil surface at the sites of background geocryological monitoring:

1 – "Belenky"; *2* – "Zagryazkin prospecting hole"; *3* – Naminga meteorological station; *4* – "Ushchelisty"; *5* – "Azarova"; *6* – "Bridge"; *7* – "Vega-23".

tive vertical gradient of the temperatures corresponds to the general tendency of warming the rock mass from above; the positive vertical gradient, on the contrary, is related to the heat loss from the depth to the surface. The absolute value of the vertical gradient is easily interpreted only for regions without phase changes during a year. This indicator seems to be more informative than the rock temperature traced down at a certain depth.

Observations over the rock temperature at the depth of 19 m suggest certain warming of the upper part of the permafrost over the recent 30 years (Fig. 7). From 1987 to 2015, the temperature variations at the depth of penetration of annual fluctuations did not exceed 1 °C. This tendency was somewhat interrupted by the temporary cooling of 2009–2012 and by the impact of the local minimum of temperatures at the depth from 40 to 100 m, which

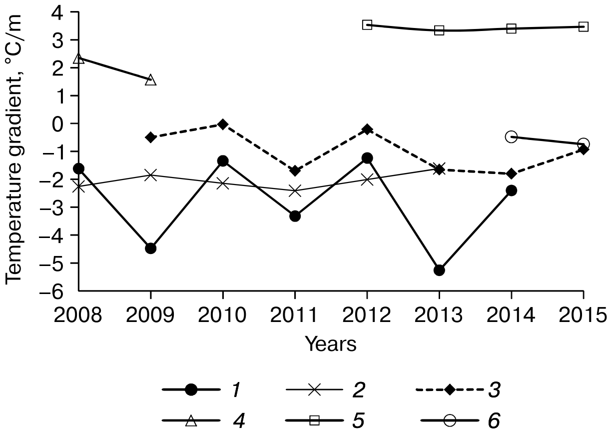

Fig. 5. Increment of the mean annual soil temperature per one meter of the depth of the active layer:

1 – "Belenky"; *2* – "Zagryazkin prospecting hole" (borehole 37); *3* – "Ushchelisty"; *4* – "Azarova"; *5* – "Sands"; *6* – borehole 41.

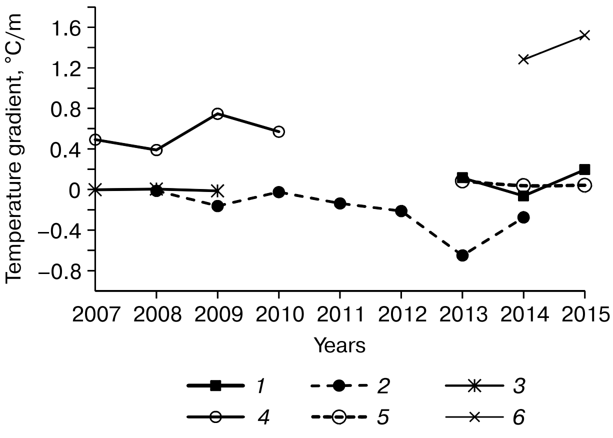

Fig. 6. Increment of the mean annual soil temperature per one meter of the depth in the near-top part of the permafrost:

1 – "Bridge"; *2* – "Belenky"; *3* – borehole 38; *4* – borehole 6; *5* – "Vega-23"; *6* – borehole 37.

occurred in the period of the recent climatic minimum [*Zheleznyak, 2005*].

MONITORING OF SEASONAL THAWING

The main result of the earth temperature monitoring consists in generating comparable data on the seasonal thaw depth or ground freezing in conditionally undisturbed landscapes of the highlands.

In the period from 2005 to 2012, we made several measurements of the depth of the seasonal thawed layer with a metal probe at the earth monitoring sites. In the summer of 2013, two observation posts for extensive monitoring were arranged at the Bridge and Belenky sites under the CALM program of the International Permafrost Association. Each site is a square with a side of 100 m, inside which an orthogonal grid is laid off with an increment of 10 m. Depths of the seasonal thawed layer were measured in the grid nodes (over 3000 measurements were made).

The Bridge site is in the central part of the Chara hollow on a tall alluvial plain of the Chara River. The surface of the site under study is even, covered with hummocks and swampy in certain spots. The upper part of the section consists of alluvial sands overlain by sand clay and peat. In August 2009, the seasonal thaw depth varied from 0.3 m (in the forest) to 0.7 m (on the dry open surface of the old river bed).

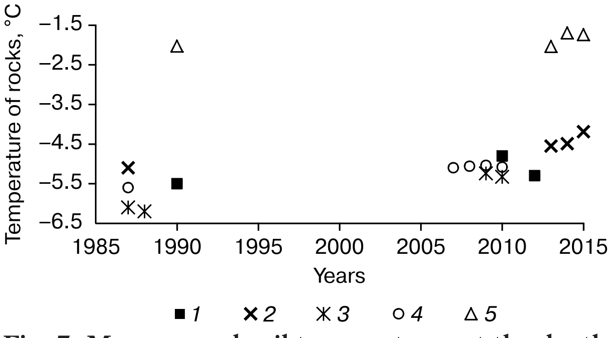

Fig. 7. Mean annual soil temperatures at the depth of 19 m:

1 – "Bridge"; *2* – "Zagryazkin prospecting hole"; *3* – borehole 38; *4* – borehole 6; *5* – "Vega-23".

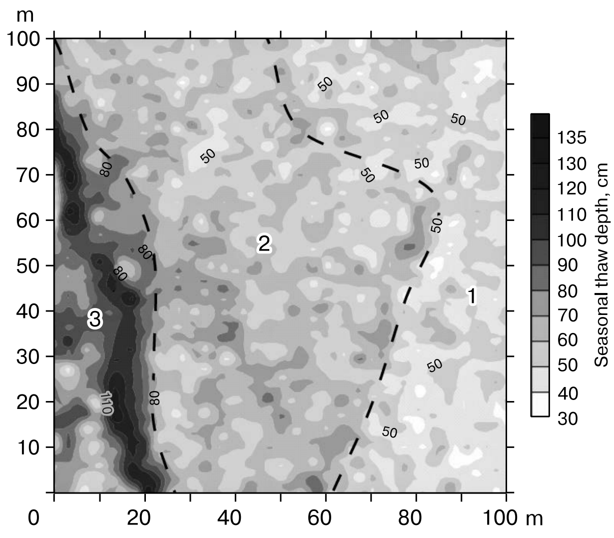

Fig. 8. Seasonal thaw depths and zoning of the heat exchange conditions over the ground surface at the "Belenky" site:

1 – forest; 2 – shrub; 3 – road (Table 2). The dashed lines stand for the boundaries of the plots.

Table 2. **Seasonal thaw depths at Belenky site**

Conditions	Vegetation	Spread rate*	*N*	Seasonal thaw depth, m				
				mean	min	max	δ	κ, %
Conditionally undisturbed	Forest	dense	501	0.48	0.31	0.72	7.4	15.5
		scarce	642	0.53	0.31	0.79	8.7	16.6
	Shrub	scarce	357	0.69	0.32	0.10	11.6	16.8
		medium	778	0.62	0.33	0.89	9.8	15.9
		thick	265	0.62	0.33	0.92	10.3	16.7
Disturbed	Road A	medium	71	0.83	0.58	0.11	11.8	14.2
	Road B	high	279	0.93	0.60	0.13	16.6	17.8
	Road C	low	189	0.68	0.39	0.94	8.9	13.2

Note. *N* – the number of measurements; δ – standard deviation; κ – variation coefficient, %.
* For disturbed conditions – the degree of impact.

The observation site Belenky is situated at the foothills of the Udokan Ridge on the first above-flood-plain terrace of the Chara River. There is a layer (from 0.2 to 2.0 m) of poorly degraded peat on top, underlain with sandy clay, up to 1.0 m thick and lower underlain with coarse gravel sands. Within the boundaries of this site, repeated-wedge ice stripped in the erosion slope of the terrace of the Chara River, is widespread. The height of the ice wedges reaches 7 m, and their width is 1.5 m. Occurrence of thermokarst is attributed to the presence of wedge ice.

At the Belenky site, the average permafrost thickness is about 0.6 m, varying from 0.3 to 1.3 m over the site. Due to inhomogeneity of the surface conditions, it was found necessary to increase the density of the observation grid, up to the increment of 1 m. By the character of vegetation and the degree of disturbance of the ground surface, the site was divided into three plots (Fig. 8, Table 2). The first plot (the conditional name “Forest”) is covered with the densest vegetation consisting of deciduous forest, shrub, and the moss-and-lichen cover of different thickness. The thawing depths are lowest here (0.3–0.5 m). On the second plot (“Shrub”) the vegetation is more scarce, consisting primarily of shrub and moss cover up to 30 cm thick. There are local traces of the old roads covered with vegetation. The permafrost thickness varies from 0.4 to 1.0 m. At the third site (“Road”), maximum seasonal thaw depths are recorded, sometimes reaching 1.3 m. The ground cover is represented by scarce moss-and grass vegetation and is often totally absent. In different parts of the site, the degree of disturbance of the ground surface varies which is reflected on division of the sire into three sub-sites Road A, Road B and Road C (Table 2).

At the Bridge site, thawing depths 0.4 to 0.8 m were recorded, with the mean value for the entire site being 0.55 m. The north-eastern part of the site contains a small portion of forest, where the thawing depth is minimal. The central and northern parts of the site have the highest water content, while its southern, south-western, and north-western parts are the driest areas.

CONCLUSIONS

As the experience has shown, it is reasonable to use the vertical gradient of the mean annual permafrost temperature fluctuations as an indicator of the total heat flow, in order to analyze the dynamic of the existing geocryological conditions. The ascertained character of the ground temperature dynamic may typify the territory under study in accordance with the vector of the geocryological processes. Therefore, BGM should be completed with observations over the spread and intensity of the geocryological processes, such as thermokarst, thermal erosion, aufeis formation, heaving, etc.

Correct interpretation of the results of thermometric observations is important to reveal the causes of activation of the geocryological processes and to expand our knowledge of their mechanism. On the surface of the river terrace, where there is Belenky site, a thermokarst has been developing over the recent decade along repeated-wedge ice patterns. In 2011, numerous new cases of subsidence emerged in many parts of the terrace, although that year was not known for the extreme values of the summer air temperatures, the atmospheric precipitation, etc. This upsurge of activity is still to be explained.

Thus, the earth temperature monitoring in itself does not provide exhaustive information on the vector of permafrost changes and should be complemented by other kinds of monitoring. Each of the observed geocryological processes should be considered in the context of territorial (background) and local variability of the environmental conditions. For example, the authors evaluated the role of geocryological conditions in the formation of the aqueous runoff of a territory [*Sergeev et al., 2009; Sergeev et al., 2012*]. The tentative analysis of the dynamic of the area of the glacial-thermokarst lakes near the Sredny Sakukan River in the Chara hollow has demonstrated varying responses of the lakes to changes in thee hydrological and climatic conditions [*Sergeev et al., 2014*]. The results of these combined studies should be analyzed jointly with the BGM data, to ensure deeper understanding of the natural processes and their prognosis.

Regarding the monitoring of seasonal thawing, it was found reasonable to conduct additional observations over the condition of the ground surface to consider annual and perennial heaving of ground. The observations revealed a complex structure of the permafrost top, not always corresponding to the micro relief, with the rate of the increment of the thawing depth also different on different micro reliefs. This rate should become the subject of regular observations.

In studying the role of geocryological conditions in the relief evolution, one should remember that, as the area of primarily or secondarily disturbed forests grows, the period of recovery of the primary forest extends [*Galanin, 2016*]. When the changes in the physical and geographical conditions are significant and it is impossible for the biotope to return to the original condition, conditionally primary communities are formed (close to the primary communities for their structure) or if the primary communities are not recovered at all [*Sukachev, 1930*]. When the anthropogenic disturbances are vast and numerous and under conditions of the global climatic changes of the end of the 20th – beginning of the 21st century, when the climate of the region changes faster than the period of transformation of the primary vegetation, the problem of determining the threshold of irreversibility of the situation becomes acute [*Chernogaeva et al., 2009; Losev, 2010; Galanin, 2016*]. Especially vulnerable to anthropogenic impact are the mountainous permafrost regions of Southern Siberia. In this regard, the importance of vegetation monitoring as a significant factor of changes in the geocryological conditions of the soil rises, as these conditions are essential for understanding the ecosystem dynamics.

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