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ACTIVE LAYER THICKNESS DYNAMICS IN THE TUNDRA PERMAFROST-AFFECTED SOILS: A CALM SITE STUDY, THE EUROPEAN NORTH OF RUSSIA

D.A. Kaverin, A.V. Pastukhov, A.B. Novakovskiy

Institute of Biology, Komi Science Centre,
28, Communisticheskaya str., Syktyvkar, 167982, Russia; dkav@mail.ru

The paper presents the results of long-term active layer monitoring (over 17 years) of mineral permafrost-affected soils on the Circumpolar Active Layer Monitoring (CALM) site in the north of European Russia (the Vorkuta area). These allowed to study the influences of climatic parameters (air temperature, precipitation) on the interannual variability of the active layer thickness and to determine the degree of the landscape factors (topography, peat layer thickness, the height of moss and shrub substories, snow depth, soil moisture) effect on spatial differentiation of the active layer thickness at local level. The tundra soils temperature regime dynamics has been characterized in relation to the long-term variability of the active layer thickness.

Tundra soils, active layer thickness, climatic parameters, landscape factors

INTRODUCTION

Permafrost-affected soils of tundra zone are characterized as highly sensitive profiles to climatic changes [*Pavlov, 1997*]. In the tundra of the Russian European North, the active layer thickness variability and soil temperature are largely governed by variations in the air temperature and snow cover depth [*Anisimov et al., 2003; Sherstyukov, 2008*].

At this, the most profound changes in the permafrost temperature field run parallel with increasing air temperature and snow cover depth. The active layer (AL) response to climate changes is determined in equal measure by the type of vegetation cover, which, itself, is involved in the warming-induced changes. The Circumpolar active layer monitoring (CALM program) is carried out with an aim to identify trends in the active layer thickness (ALT) variability inherent in permafrost-affected soils and to analyze their correlation with climate and landscape parameters [*Klene et al., 2001*]. Activities of a total of 110 CALM monitoring sites are unified by measurement protocol ensuring statistical reliability of the obtained data [*Brown et al., 2000*].

In the past two decades, the most pronounced trends in the progressively increasing seasonal thaw depth (i.e. active layer thickness) have been observed in the European North, a region particularly sensitive to climate change in our country [*Mazhitova et al., 2004b; Oberman and Shesler, 2009*]. At present, there are three CALM sites in the region whose intermediate monitoring results were published earlier [*Mazhitova et al., 2004a; Mazhitova and Kaverin, 2007; Malkova, 2010*], which indicated a significant growth rate of the thaw penetration depth of permafrost horizons already in the 2000s.

The paper presents and discusses results of the active layer thickness (ALT) monitoring in the period between 1998 and 2015 at the CALM R2 site located in the vicinity of the town of Vorkuta [*GTN-P, 2016*]. The monitoring site CALM R2 is a specific research object, where permafrost deposits occur in the shallow subsurface (at a depth of about 1 m) in the conditions of tundra soils in the southern part of European permafrost zone. The aim of this research is to evaluate the influences of climatic parameters and landscape factors on the active layer thickness of the tundra permafrost-affected soils by the example of a monitoring site in the permafrost zone (north-east of Russian European).

OBJECTS OF RESEARCH

The study site is located in the eastern part of the Bolshezemelskaya tundra – the area of wide distribution of massive-island permafrost [*Yershov, 1988; Yershov and Kondratieva, 1998; Oberman and Mazhitova, 2001*], which is a shallow valley, covered with a mantle of silty clay-loams with a thickness <10 m [*Enokyan, 1959*]. According to geobotanical zoning, the area belongs to the subzone of the southern tundra characterized by the growth of high shrubs and widely developed peatland plateaus. According to the Vorkuta weather station (WS) data, the mean annual air temperature (MAAT) for the period of 1947–2015 constituted –5.6 °C, the sum total of mean daily air temperatures above 0 °C averaged 1021 °C, the average annual precipitation totaled 517 mm. The climate parameters estimated for the research period are listed in Table 1. During the period of our observations (1998–2015), MAAT showed a slightly increasing trend (linear regression (LR) coefficient is positive; significance level p = 0.116, determination factor R^2 = 0.156) (Fig. 1).

Table 1. **Climate parameters dynamics over the period of 1998–2015 (the Vorkuta weather station data)**

Hydrologic year	Mean annual air temperature, °C	Thaw Degree Days, °C·day	Freeze Degree Days, °C·day	Total of annual precipitation, mm	Total precipitation for warm period (May–September), mm	Total precipitation for cold period (October–April), mm	Average snow depth for the monitoring site*, cm
1998/99	–8.4	881	–3930	541	314	227	39
1999/00	–3.9	1191	–2609	467	233	234	30
2000/01	–5.3	1235	–3156	433	186	247	31
2001/02	–6.1	882	–3099	552	337	215	40
2002/03	–5.7	1245	–3309	613	309	304	31
2003/04	–4.8	1193	–2871	483	231	252	41
2004/05	–4.0	1291	–2723	525	274	251	41
2005/06	–4.3	1107	–2630	597	328	270	33
2006/07	–3.7	1277	–2464	489	249	240	52
2007/08	–3.6	1126	–2322	525	219	306	43
2008/09	–4.5	1046	–2604	613	282	331	43
2009/10	–7.0	995	–3542	776	404	372	43
2010/11	–4.1	1098	–2562	668	247	421	39
2011/12	–2.3	1370	–2182	642	336	306	44
2012/13	–4.8	1200	–2951	438	218	220	50
2013/14	–5.5	873	–2862	623	322	301	88
2014/15	–3.8	1184	–2566	517	263	254	62
Average over the period of 1998–2015	–4.8	1129	–2846	559	279	279	44
Coefficient of correlation with AL thickness	0.4	0.2	0.5	0.3	0.1	0.4	0.4

*The data from snow survey at CALM R2 site.

Notably, a rise in the mean annual temperatures was dictated by a measurable variation in the freezing degree days (FDD) (LR coefficient 41.422, $p = 0.05$, $R^2 = 0.233$). While the thawing degree days (TDD) did not show any marked variations (LR coefficient 1.665, $p = 0.851$, $R^2 = 0.002$).

The Ayach-Yakha CALM R2 site located 13 km north-east of the town of Vorkuta (67°35′ N; 64°10′ E) belongs to the tundra landscape with permafrost-affected soils, which are common in the Bolshezemelskaya tundra, occupying about 15–20 % of the study area featured by low-snow (windward) gentle slopes and summits of ridges with moss-shrub tundra; evidences of spotted frost heave; and the ALT ranging within a meter.

The total soil profile thickness within the investigated landscape generally coincides with the active layer thickness. The site designated for landscape characterization covers the area of about 0.1 km^2, encompassing the gentle south-west-facing slope of the hill with a maximum absolute elevation of 184.8 m (a.s.l.) and in excess of 45 m above the water edge in Staryi stream [*Mazhitova and Kaverin, 2007*]. A comparative characteristic of soil temperature regimes for various landscapes of the study area is discussed in several contributions [*Kononenko, 1986; Mazhitova, 2008; Kaverin et al., 2014*]. The monitoring site 100 × 80 m in size is established as a network of permanent observation points with a grid size 10 × 10 m. The site is located on a slightly inclined surface (inclination angle: about 3°, SSW-exposure) with a height difference of 5 m. Vegetation is mossy-shrubby tundra with frost-heave spots, soils are represented by peat-gley cryogenic soil.

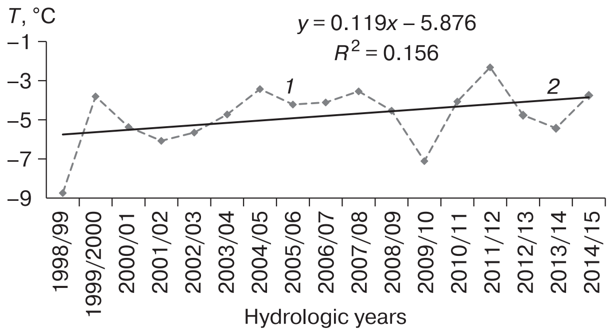

Fig. 1. Mean annual air temperature dynamics (Vorkuta weather station).

1 – mean annual temperature; *2* – linear trend.

RESERACH METHODS

Instrumental measurements. The active layer thickness (ALT), i.e. the maximum depth of seasonal ground thaw, has been measured at the site every year since 1996 at each of 99 points, with measurements taken using a graduated metal gauge. Noteworthy is that at the time when the site was put in operations, it counted a total of 121 grid nodes, however, during first years of measurement, two rows of stakes located at the slope foot were excluded from the site, given that within the area marked by those stakes, the seasonal thaw penetration reached the bedrock (depth: 1.0–1.5 m) as early as the beginning of the 2000s, which cancelled out any expediency of further measurements. Beginning from 1999, an additional complex of measurements including snow surveys, soil moisture measurements and topography changes surveys were carried out at the site every year, which enabled evaluation of the impacts from landscape factors at the depth of seasonal thaw penetration.

Measurements of volumetric moisture content in the 10-cm topsoil layer is carried out using the Delta-T SM 150 electronic moisture meter furnished with a versatile readout unit HH2. Since 1999, absolute elevations of the soil surface have been determined at all of the 99 permanent points during the warm season marked by the beginning (May) and end (September), in order to detect any variations in the study site topography. The measurements are carried out using the Geobox N8-32 optical level, giving an error of 1.5 mm per 1 km of return run. The multiyear surface observations within the site area enable monitoring of the frost heave/subsidence dynamics on the surface of permafrost-affected soils.

The long-term temperature measurements (1998–2015) were taken with the HOBO U-12-008 digital temperature data loggers programmed for 8 measurements/day to record the AL soil temperatures at a depth of 0, 20 and 50 cm. The logger sensors are mounted on a wooden pole installed in a wellbore (hole) 3 cm in diameter and 50 cm deep. The measuring accuracy of temperature sensors is 0.21 °C. In September 2015, single soil temperature measurements were taken at a depth of 20 and 50 cm, at all observation points of the site, using a portable HANNA HI 935005 thermometer complexed with HI 766TR2 penetrating probe (accuracy: up to 0.1 °C). At this, the temperature data from the logger installed at C5-point of the site showed a good agreement between the results of single (sporadic) and monitoring measurements. The peat horizon thickness and the height of subshrub-shrub and moss understories in the site area were measured in September 2011.

Statistical data processing. The interplay of climatic and landscape parameters affecting both temporal and spatial variability of the active layer thickness was estimated using correlation coefficients, and the multiregression analysis method (GLM – General Linear Model) [*Dobson, 2002*]. For evaluation of the climate change impact indicators, the correlation coefficient was calculated for each specific point (stake) over the entire observation period. The influences of landscape indicators were estimated by correlation between all points and landscape indicators for each individual year.

In the multiregresion analysis, the active layer depth acted as a dependent variable in the model. Predictors (independent variables) contained in the model were represented by the seven landscape factors listed below: 1) absolute elevations of the test site surface (elevation above sea level; range: 5 m); 2) microrelief (deviations of the absolute elevation marks of the site surface along the slope line approximation (range: 0–1.2 m); 3) peat layer thickness in the soil horizon (range: 4–20 cm); 4) height of moss cover (range: 0.2–5.0 cm); 5) height of the subshrub-shrub understory (range: 5–60 cm); 6) the depth of snow cover (range: 0–123 cm); 7) volumetric moisture of the topsoil layer (range: 0–100 %), and four climatic factors (TDD, FDD, and total precipitation over the cold and warm periods).

All indicators are continuous and used as covariates of the linear model. Landscape variables that have significant gaps (more than 50 %) were excluded from the linear model for the related year within the series of years. The quality of the resulting models was evaluated on the basis of the Fisher value (F) and corresponding level of significance (p). It should be noted that not all the analyzed data obeyed normal distribution, which nevertheless is a necessary condition for regression modeling and correlation analysis. Therefore, the authors used a bootstrap analysis, instead [*Shitikov and Rosenberg, 2013*], seeing as it belongs to the so-called computer-intensive technologies and does not require a priori information on the analyzed indicators distribution. The approach consists in repeating all the calculations a large number of times (usually 1000–10 000) under almost identical conditions in the original data (i.e. with insignificant variations). This results in forming a sample for each regression or correlation coefficient, which allows to determine corresponding level of significance. As such, this analysis is computationally less demanding to the initial data, than the standard asymptotic approaches.

The contribution of the analyzed characteristics to the total variation of the dependent variable was estimated by the formula

$$D_i = \frac{SS_i}{\sum SS_i} R^2 \cdot 100\,\%,$$

where D_i is the fraction of variance in variability of the dependent parameter explained by the i-th factor; SS_i is the sum of squared deviations of the variable dependent on the values the model predicted without account of i-th parameter (the contribution from i-th factor into general model); R^2 – determination coefficient (the fraction of variance explained by the model).

Conventional values for the microrelief were calculated for determining the heterogeneity of the site surface located on the slope. The values for microrelief were calculated by the multi-regression analysis method (independent variables are the point's coordinates along the x and y axes; the dependent variable is the elevation mark of the observation point). Then, the plane optimally approximating the slope which accommodates the site, is calculated. Deviations in elevation marks of the observation points from this calculated slope were interpreted to be a quantitative characteristic of the mesorelief. As such, this method is not universal, however, it is applicable to insignificant differences in elevations.

At this, positive deviations correspond to the convex elements of the relief, whereas negative – to concave elements. Note that the landscape factor is termed "microrelief" only conventionally, inasmuch as it provides basic characteristics of heterogeneity of the slope surface. All calculations were carried out using the IBM SPSS Statistics 19 software. Significant coefficients with significance level $p < 0.05$ were considered statistically significant. For the purpose of the research results visualization, the cartograms for the monitoring area reflecting spatial differentiation of the active layer thickness and landscape factors are compiled in the GoldenSoftwareSurfer 8 software package.

RESULTS AND DISCUSSION

The active layer thickness dynamics. The average seasonal thaw penetration depth progressively increased throughout the site area in the period from 1999 to 2007. The increasing trend for the active layer thickness became weak and statistically insignificant in the 2008–2015 period, though. A decrease in the average ALT is reported from the periods 2007–2009 and 2013–2015. The active layer thickness averaged over the site area for the entire observation period (1999–2015) was (82 ± 11) cm. In 2015, the average ALT within the site totaled up to 139 % (89 cm) of the 1999-year value (64 cm) (Fig. 2).

In 1999, as little as 1 % of the observation points reported ALT > 1 m, while in 2015 this indicator increased to 17 % (Fig. 3). The permafrost occurrence depth <1 m is one of the main classification criteria for classifying soils within a group of permafrost-affected soils (Cryosoils) [*IUSS..., 2014*]. The coefficient of variation in the active layer thickness in 1999 was 19 %, in 2015 – 16 %.

Climatic parameters effects on the active layer thickness. Averaged over all points, the active layer thickness/climatic factors correlation coefficients

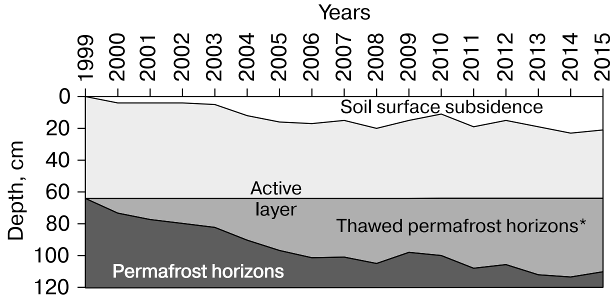

Fig. 2. Active layer thickness dynamics at the CALM R2 site (1999–2015).

* Thicknesses of the thawed permafrost horizons – since 1999.

at the 5 % level were found to be statistically insignificant. The highest correlation coefficients (r = 0.4 ± 0.2) averaged over all observation points of the site were revealed between the active layer thickness and such climatic parameters as the mean annual air temperature, FDD (freezing index), and the snow cover depth. The annual total amount of precipitation and the sum of precipitation during the warm period have shown even weaker correlation with ALT (0.3 ± 0.2 and 0.1 ± 0.1, respectively).

Minor correlations (r = 0.2 ± 0.2) are revealed with a thawing index (TDD). In the previous research [*Mazhitova and Kaverin, 2007*], the authors noted a statistically significant correlation (r = 0.6) between the ALT and TDD. The observed differences are accounted for calculations in the previous studies covering a period of continuous increase in ALT (1996–2007). However, in recent years (2007–2015), the influence of winter temperatures on active layer thickness has become more appreciable.

Analysis of the spatial variability of the ALT/MAAT correlation coefficients have shown that statistically significant coefficients are characteristic only for 25 % of observation points (Fig. 4). The maximum number of observation points with statistically significant correlation coefficients was remarkable under a significant impact from the snow cover (44 %). Analysis of spatial variability of the climatic factors/the active layer depth correlation coefficients have revealed a discernible locality with negative coefficients at the site (Fig. 4) confined to a well-drained runoff channel wall, which hardly showed any increase in the active layer thickness, nor evidence of the soil surface subsidence during the research.

The multi-regression analysis, conducted for a combination of climatic factors, accounts for 47 % of the interannual variation in the active layer thickness. The "FDD" parameter explains the largest fraction of the variance, whereas the sum total of precipitation for the cold period influences it to a lesser extent (Table 2). The increasing winter temperatures aggravated by an increase in the snow cover depth

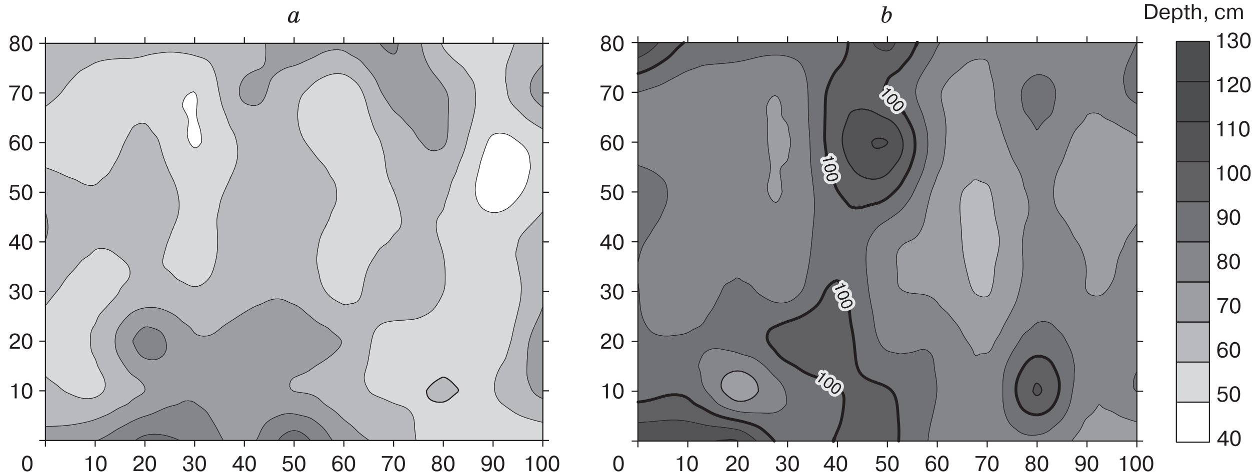

Fig. 3. Active layer thickness at the CALM R2 site.
a – 1999; *b* – 2015.

preclude complete freezing of the active layer during the winter. A decrease in "accumulation" of the winter chill in soils, in turn, facilitate the faster thawing of soils in the summer.

The landscape factors effects on active layer thickness. Among the landscape factors, the thickness of the peat horizon of soils exerts the greatest influence on the active layer thickness. The average correlation coefficient for the site area was $r = -0.40 \pm 0.04$. The fraction of the explained variance for the peat horizon also appeared to be the biggest (Table 3). Note that the average active layer depth at the observation points with an organogenic horizon with thickness at least 10 cm was 85 cm, while at greater peat thicknesses it was 78 cm. The peat-gley cryogenic soils, as compared with automorphic profiles, are characterized by a colder temperature regime and, accordingly, a lesser active layer thickness in the region [*Mazhitova, 2008; Kaverin et al., 2014*].

Smaller averaged correlation coefficients ($r = -0.2 \pm 0.2$) are characteristic for such factors as absolute altitude, microrelief and moss layer thickness. The soil moisture content has a positive average coefficient $r = +0.2 \pm 0.2$. The correlation coefficient, reflecting the snow cover impacts, varies in a wide range from –0.3 to +0.3, averaging 0.0 ± 0.2. In this case, negative correlation coefficients resulted for years with a lower average snow depth (30–40 cm), revealing no interrelation with the vegetation height ($r = 0.0 \pm 0.05$). For a more correct and accurate assessment, the multi-regression analysis was used allowing for the combined effect of landscape factors on the spatial differentiation of the active layer thickness. Its results showed that the constructed linear regression models for each of the investigated years are adequate (F-statistics values are in the range between 2.56 and 7.04, all significance levels $p < 0.05$) (Table 3).

The determination coefficients R^2, describing the level of explained variability of the indicator (active layer thickness) dependent on the landscape indica-

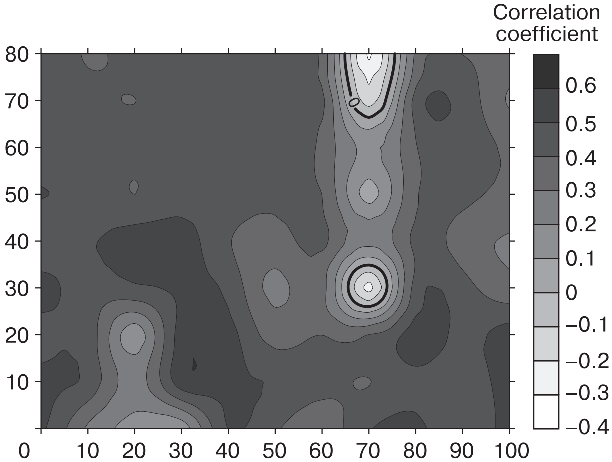

Fig. 4. Coefficients of correlation between mean annual air temperature and active layer thickness at observation points of the monitoring site.

Table 2. **Effect of climate parameters on interannual variability of average active layer thickness within the monitoring site area**

Climate parameter	Fraction of explained variance, %	p (bootstrap analysis)
Thaw Degree Days	0	0.913
Freezing Degree Days	30	0.059
Total precipitation for warm period (May–September)	5	0.354
Total precipitation for cold period (October–April)	12	0.211

Table 3. **Effects of landscape factors on active layer thickness according to multiregression analysis results**

Parameter	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Macrorelief																	
D_i	6.9	6.6	0.0	6.1	4.1	2.7	6.0	4.0	**16.2**	5.7	0.6	0.1	4.3	5.2	7.0	0.5	3.0
p_i	0.11	0.16	0.95	0.18	0.19	0.32	0.09	0.21	**0.01**	0.14	0.61	0.87	0.16	0.15	0.10	0.73	0.31
sgn	–	–	+	–	–	–	–	–	–	–	+	–	–	–	–	+	–
Mesorelief																	
D_i	3.6	1.8	**17.8**	0.0	5.1	0.2	4.2	2.4	1.0	2.6	**19.8**	**12.5**	5.0	**20.0**	**15.9**	12.4	6.8
p_i	0.24	0.47	**0.02**	0.99	0.14	0.80	0.16	0.33	0.51	0.32	**0.00**	**0.03**	0.13	**0.01**	**0.01**	0.10	0.13
sgn	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Thickness of peat horizon																	
D_i	**29.6**	**28.5**	**22.1**	**30.5**	**27.9**	**29.4**	**23.0**	**26.0**	**23.6**	**14.2**	**17.4**	**30.5**	**22.0**	**22.9**	**23.3**	**17.4**	**18.7**
p_i	**0.00**	**0.00**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.02**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.05**	**0.01**
sgn	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Moss thickness																	
D_i	0.9	0.0	0.4	0.8	0.0	1.3	0.4	0.2	4.0	3.2	4.0	3.3	2.5	2.3	5.3	2.1	0.2
p_i	0.55	1.00	0.71	0.63	0.98	0.49	0.65	0.77	0.19	0.27	0.18	0.26	0.29	0.34	0.15	0.49	0.81
sgn	–	+	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Vegetation height																	
D_i	3.8	0.0	1.6	1.2	1.9	3.2	2.5	0.5	2.1	0.0	0.3	0.0	0.7	0.0	0.0	0.1	0.5
p_i	0.23	0.91	0.47	0.56	0.37	0.27	0.27	0.66	0.34	0.90	0.73	0.89	0.58	0.98	0.89	0.89	0.67
sgn	–	–	–	–	–	–	–	–	–	–	+	–	–	+	+	–	–
Snow depth																	
D_i	n.a.	5.7	0.1	0.7	6.2	0.0	1.0	0.5	0.1	8.5	5.4	n.a.	0.0	1.6	0.4	5.3	**17.6**
p_i	n.a.	0.20	0.84	0.65	0.11	0.99	0.49	0.66	0.81	0.07	0.12	n.a.	1.00	0.42	0.69	0.28	**0.02**
sgn	n.a.	–	–	+	–	+	–	–	–	+	–	n.a.	+	–	–	+	+
Soil moisture content																	
D_i	0.6	n.a.	3.1	0.6	8.2	**13.1**	**23.1**	**22.8**	6.8	**25.1**	n.a.	n.a.	**23.0**	n.a.	n.a.	n.a.	0.3
p_i	0.63	n.a.	0.32	0.68	0.06	**0.03**	**0.00**	**0.00**	0.09	**0.00**	n.a.	n.a.	**0.00**	n.a.	n.a.	n.a.	0.76
sgn	+	n.a.	+	–	+	+	+	+	+	+	n.a.	n.a.	**+**	n.a.	n.a.	n.a.	+
df	87	92	98	97	98	95	97	97	98	98	98	98	98	98	98	98	98
R^2	44.7	42.6	45.2	39.8	53.4	49.9	60.2	56.5	53.9	59.5	47.4	46.5	57.4	52.1	51.8	37.8	47.2
F	3.74	3.39	3.33	2.43	5.18	4.16	7.32	6.02	5.31	7.04	4.43	5.12	6.39	5.7	5.7	2.56	3.72
p	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0.02	0

Note. D_i – fraction of explained variance; p_i – significance levels; sgn – sign for coefficient of ALT variability in relation to landscape factors; *df* – number of degrees of freedom for the model (sample number – 1); R^2 – pooled variance, explained by GLM-model; F – Fisher's variance ratio; p – overall significance level of the model; n.a. – the data are either not available or insignificant, the parameter is not included in the analysis. Significant parameters are given in bold type.

tors, are in range from 37 to 59 %. The average R^2 value being 50 %, this proved to be a good indicator for the data obtained during the field measurements. The most pronounced dependence appears between the active layer and the thickness of peat layer in the horizon of soils (Table 3). In 16 out of 17 constructed GLM-models, the regression coefficient of this parameter has proven to be significant ($p < 0.05$). The fraction of the explained variance for this indicator varies in the range of 14–30 %, considerably exceeding other factors.

The absence of significant dependence is observed only for 2014, when the GLM-models showed the lowest values of convergence (F = 2.56, p = 0.02). A high proportion of significant linear regression coefficients in GLM-models was remarkable for mesorelief and soil moisture (Table 3). For both of the factors (predictors), 5 out of the 17 coefficients are significant. However, the fraction of the explained variance for these indicators are by far lower: 0–20 % for microrelief and 0–25 % for soil moisture.

Note that for such factors as microrelief and the peat horizon thickness, the dependence is inverse: the greater the thickness of peat and the deviation of absolute elevations from the approximating linear slope, the lesser the active layer thickness of soils. Soil moisture content shows a direct dependence on ALT, which is associated with an increase in the thermal conductivity of soil with increasing moisture content [*Yershov, 2002*]. Other landscape factors do not exert any measurable effect on ALT; significant values of their regression coefficients are reported occasionally.

Temperature regime of soils and active layer thickness. The total range of average annual soil temperatures at depths of 0, 20, 50 cm in the investigated soils was 2.2...–3.5 °C (Table 4). Negative mean annual temperatures are characteristic, for the most part, of permafrost-affected soils, and positive represent non-affected soils [*Kudryavtsev et al., 1981; Burn, 2004*]. The positive average annual temperature in the upper soil horizons, when it is negative at other depths (temperature offset), is one of the signs of degradation of permafrost [*Burn, 2004*]. A significant increase in the permafrost-affected soil temperature was established at the monitoring site over the past two decades [*Mazhitova, 2008; Kaverin et al., 2014*]. The internal permafrost-affected soil climate has become much milder over the research period, with the temperature parameters approaching those for the tundra long-term seasonally frozen (non-permafrost) soils [*Kaverin and Pastukhov, 2017*].

FDD for the peat-gley cryogenic soil surface ranged from –169 to –1999 °C·day. During the observation period, FDD values have notably reduced in the upper part of the soil profile (Table 4). The maximum soil cooling was reported during the 1998/99 hydrologic year, when FDD totaled –3930 °C·day (by 29 % colder than the average multi-year norm for 1947–2015). TDD values at a depth of 0 cm for all the years of observations totaled up to 493...1045 °C·day (Table 4). There was no statistically significant increasing trend for TDD at the surface; the most pronounced increasing temperature trend (R^2 = 0.5) was observed only at a depth of 50 cm. During the study period, an increase in ALT was therefore concomitant with a gradual increase in soil temperatures. At the same time, coefficients were found to be statistically significant for correlation between seasonal thaw depth and such parameters as the mean annual temperature and the sum of negative soil temperatures (Table 4).

TDD has a measurable impact only at a depth of 50 cm, which is accounted for the proximity of the cooling permafrost shield. In the surface horizons, the temperature regime of soils reflects predominantly the air temperature impacts during the vegetative period. Single measurements of soil temperature within the site area in September 2015 showed a spatial differentiation of the temperature field within the monitoring site (Fig. 5). The coefficients of correlation between the spatially inhomogeneous soil temperatures and the depth of thawing were 0.3 at a depth of 20 cm and 0.6 at 50 cm depth. Higher soil temperatures were observed in the lower part of the valley and along the central median of the site. These segments of the study site were characterized by a lower peat layer thickness in the soils horizon.

The research period was marked by the maximum rates of augmented seasonal thaw and subsidence of the soil surface. The degradation of the closely occurring mineral permafrost soils in the southern

Table 4. **Main soil temperature parameters for Histic Cryosols at CALM R2 site in the period of 1998–2015**

Hydrologic year	Mean annual temperature (°C) at depth			Sum of negative air temperatures (°C·day) at depth			Sum of positive temperatures (°C·day) at depth		
	0 cm	20 cm	50 cm	0 cm	20 cm	50 cm	0 cm	20 cm	50 cm
1998/99	–3.5	–	–3.4	–1999	–	–1315	789	–	149
1999/00	–0.2	–	–	–955	–705	–	493	313	–
2000/01	–1.0	–1.8	–1.8	–872	–691	–769	622	–	100
2001/02	–	–	–1.9	–1034	–	–781	–	–	124
2002/03	–0.8	–1.9	–1.8	–1122	–1001	–861	862	315	190
2003/04	–	–	–0.6	–591	–	–370	–	–	136
2004/05	–0.6	–	–0.9	–878	–654	–529	–	–	206
2005/06	–	–0.4	–0.5	–785	–577	–470	–	443	283
2006/07	1.7	2.3	–	–340	–	–	961	–	–
2007/08	–	1.1	0.9	–	–118	–13	–	510	333
2008/09	0.9	0.2	–0.4	–394	–226	–278	721	311	122
2009/10	0.2	0.0	–0.3	–474	–253	–202	541	266	101
2010/11	1.0	0.7	0.6	–385	–206	–197	743	452	419
2011/12	2.1	1.3	1.3	–169	–57	–57	935	518	525
2012/13	1.4	0.5	0.5	–402	–241	–224	900	429	414
2013/14	1.0	0.5	0.6	–211	–88	–90	582	290	315
2014/15	2.2	1.3	0.9	–252	–109	–32	1045	563	355
Coefficient of correlation with AL thickness	0.9	0.8	0.9	0.9	0.8	0.9	0.3	0.4	0.7

Note. Dash (–) stands for unavailable values.

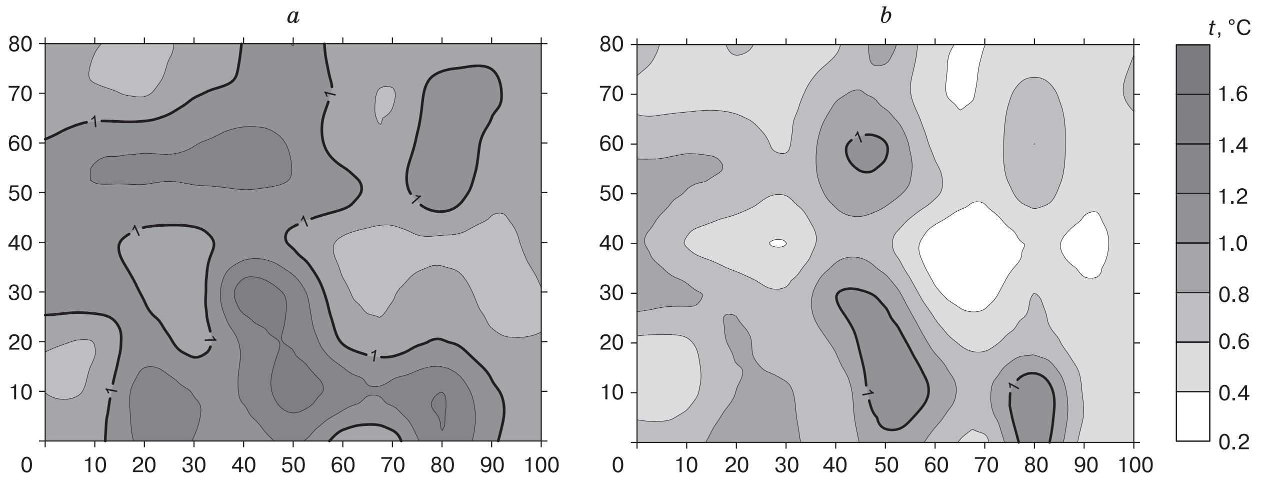

Fig. 5. Soil temperature (t) at CALM R2 site (23.09.2015).

a – at a depth of 20 cm; *b* – at a depth of 50 cm.

tundra is primarily associated with sites with the lowest thickness of the heat-insulating peat horizon. Areal measurements of temperature of the tundra permafrost-affected soils within a meter enables detection of "high-temperature" zones, characterized by the largest long-term surplus in the seasonal thaw penetration depths.

CONCLUSIONS

In the observation period (1999–2015), the interannual variability of the AL depth was most affected ($p = 0.059$) by winter climatic parameters, determining both the depth and rate of soil freezing: FDD (30 % of the explained variance) and total precipitation during the cold period (12 %).

At a local level, spatial differentiation of the active layer thickness is largely governed by inhomogeneous thickness of the peat horizon of soils (24 ± 5 % of the explained variance). To a lesser extent, however, at a statistically significant level ($p < 0.05$), the ALT is affected by microrelief (8 ± 7 %) and soil moisture (10 ± 7 %).

Other landscape factors (absolute surface height (5 ± 4 %), snow depth (4 ± 5 %), height of moss cover (2 ± 2 %) and subshrub-shrub substory (1 ± 1 %)) are of little effect on the spatial differentiation of seasonal thaw depth.

The internal permafrost-affected soil climate has become much milder over the study period: the average annual soil temperature increased from −1...−3 °C over the period of 1999–2000 up to +1...+2 °C in 2014–2015. The active layer thickness showed a significant ($p < 0.05$) correlation with the variation in FDD and the average annual soil temperature ($r = 0.9 \pm 0.1$). Besides, rising temperatures of soils during the winter-season preclude the active layer freezing completely throughout the winter.

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