RESEARCH PAPER

ACTIVE LAYER DYNAMICS NEAR NORILSK, TAIMYR PENINSULA, RUSSIA

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ABSTRACT. This paper provides information on active layer thickness (ALT) dynamics, or seasonal thawing above permafrost, from a Circumpolar Active Layer Monitoring (CALM) site near the city of Norilsk on the Taimyr Peninsula (north-central Siberia) and the influences of meteorological and landscape properties on these dynamics under a warming climate, from 2005 to 2020. The average ALT in loamy soils at this 1 ha CALM site over the past 16 years was 96 cm, higher than previous studies from 1980s conducted at the same location, which estimated ALT to be 80 cm. Increasing mean annual air temperatures in Norilsk correspond with the average ALT increasing trend of 1 cm/year for the observation period. Active layer development depends on summer thermal and precipitation regimes, time of snowmelt, micro-landscape conditions, the cryogenic structure (ice content) of soils, soil water content leading up to the freezing period, drainage, and other factors. Differences in ALT, within various micro landscape conditions can reach 200% in each of the observation periods.

KEYWORDS: Active Layer Thickness (ALT), permafrost, thaw subsidence, CALM (Circumpolar Active Layer Monitoring) program, Russia, Taymyr Peninsula

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INTRODUCTION

The active layer is a soil or rock layer between the ground surface and permafrost that thaws in the summer season and freezes again in the winter (General Permafrost Science 1978). Active layer thickness (ALT) is highly variable owing to high spatial variability in vegetation and soil conditions, local topography, and geomorphic conditions. ALT is recognised as one of the most important variables used to characterise the permafrost system and its response to climate change (French 1999). Determination of ALT in various landscapes and soils is also a necessary step in many engineering and geocryological surveys, as well as in ecosystem studies. The active layer is sensitive to changing climatic conditions and can be used as an indicator for the assessment of the state and rate of transformation of permafrost (Kudryavtsev 1954; Shur 2005).

Detailed studies of ALT variability have always been at the center of permafrost research, including pioneering works by V. Kudryavtsev, V. Tumel, I. Redozubov, G. Feldman, A. Pavlov, D. Gilichinsky, N. Tumel, A. Washburn, J. Brown, T. Péwé, F. Nelson). Previous studies established patterns of ALT and factors influencing ALT dynamics, revealed its role in determining the stability of engineering structures built on permafrost, and provided an assessment of settlement of thawing or heaving during the freezing season.

Active layer dynamics depend on the climatic, landscape, and soil conditions characteristic of specific areas (Nelson et al. 1998). The Circumpolar Active Layer Monitoring Program (CALM) was created in 1991 to track long-term changes in ALT. It currently includes more than 250 active sites with standardized observations in permafrost regions of both hemispheres (Brown et al. 2000; Nelson et al. 2021).

This report is focused on a CALM site established in the north of central Siberia (Taimyr), near city of Norilsk in 2005. The site is among the locations where changes in climatic and near-surface permafrost temperature are most pronounced in recent years (Streletskiy et al. 2015). In this paper we evaluate the spatial and temporal variability of the active layer within the Western Taymyr region, particularly Norilsk. The study is based on data collected at the Norilsk CALM site over 16 years and assesses the role of rapidly changing climatic conditions and landscape transformations on active layer dynamics.

Background

The first known report on the conditions of the active layer in the region is attributed to the first geological expedition led by N.N. Urvantsev in the valley of the river Norilskaya in 1918, which reported difficulties in transporting cargoes by carts as they became mired repeatedly in thawed loamy-clayey soils. However, the report noted that excavation of soil pits was much easier in the thawed layer, as compared to frozen soils. The first instrumental measurements of active layer thickness in this area were conducted in the 1920s and 1930s by the Northern Sea Route Committee on the route of the proposed Dudinka – Norilsk railway. Measurements were unsystematic and were made in different periods during the summer season. Construction of the Norilsk Mining and Metallurgical Plant was initiated in 1935, and created high demand for engineering and geological surveys. Specialists from the Committee for the Study of Permafrost of the Academy of Sciences of the USSR arrived in Norilsk in 1936 under the leadership of V.F. Tumel, who organized a special group under the management of NorilskStroy. A laboratory for the study of physical and mechanical properties of soils and a permafrost station under the leadership of engineer M.V. Kim were organized. This group paid particular attention to the permafrost mechanical properties and permafrost temperature regime of foundations and basements. The employees of the permafrost laboratory collected information about the depth of thawing in various types of soils, which allowed estimation of the range of the maximum depth of seasonal thawing of soils (depending on soil type, the impact of groundwater, vegetation, etc.) from 0.5 to 3.5 m (Sheveleva, Khomichevskaya 1967). In later work it was noted that the smallest depths of seasonal thawing in the Norilsk region were typical for floodplains and terraces covered with peat, and are 0.3 to 0.8 m; maximum thickness was from 4.5 to 5.5 m on gently sloping areas of the plateau, which is composed of highly fractured, highly conductive basalts covered by thin (up to 0.5 m) Quaternary sediments (Demidyuk 1989). Thaw depth data were obtained during thermal measurements in boreholes by interpolation to determine the depth of the 0°C isotherm.

No regular observations of ALT dynamics were conducted before the start of measurements within the framework of the Circumpolar Active Layer Monitoring program (CALM). The CALM program utilizes various methods to determine ALT, and detection of the surface elevation to estimate the effect of the winter heaving and subsequent thaw subsidence (Brown et al. 2002).

Results obtained through the CALM program demonstrate strong spatial heterogeneity in ALT worldwide (Luo et al. 2016; Abramov et al. 2019). Regional research conducted in the Putorana Plateau near Norilsk shows expansion of forest vegetation due to an increase in winter precipitation during the 20th century (Kirdyanov et al. 2012). A case study based on remote sensing (Nyland et al. 2017) showed that maximum changes (17%) occurred in closed forest areas. These closed forest areas experienced rapid tree growth and expansion of shrubs, while open forest expanded with individual trees up to 20 m apart and herbaceous and moss layers between. Numerous studies conducted in West Siberia have also documented expansion of southern species into the northern territories. One of the most dramatic changes is the replacement of the southern tundra by forest-tundra (Moskalenko, 2003; Vasiliev et al. 2021; Frost et al. 2019). Such change is usually connected with increases in average annual air temperature and subsequent increases in permafrost temperature.

For engineering purposes, specialists from the Norilsk permafrost laboratory experimentally produced data on the potential thaw settlement of thawing soils in the area (Sheveleva, Khomichevskaya 1967). Potential thaw settlement varies over a wide range, from 0.5-2 %/m for fluvial-gravel pebbly rocks; 10-20 %/m- for lacustrine loams; and up to 48 %/m in icy lacustrine clays dominated by ground ice. Subsidence was studied in the laboratory using frozen soil samples. However, in natural conditions the process is more complicated by patterns of water drainage in the active layer and the high variability of soil conditions. Ground subsidence in tundra landscapes depends on weather conditions in particular warm seasons and on ice content (Streletskiy et al. 2017).

Study Area

The geographic location of the site is shown in Figure 1. The site is on the Taimyr Peninsula of northern Siberia, in the Norilsk-Rybninskaya valley, 1 km south of the Kharaelakh Mountains, part of Putorana Plateau. The site is 2.5 km southeast of the Talnakh city part of the Norilsk industrial area of the Krasnoyarskiy Kray. The site is located within the Valkovskaya lacustrine-alluvial valley terrace, on the watershed surface between two streams and has a slight (1-2^{o}) slope in the southwest direction. The formation of the terrace is associated with the drainage of a lake known as Valyok Basin at the end of the Late Pleistocene. Lake drainage resulted in accumulation of loamy-clayey sediment, in which formed ice-rich permafrost (Sheveleva and Khomichevskaya 1967). The valley is bordered by the steep spurs of the Putorana Plateau located 1 km northeast from the R-32 site. The plateau protects the study area from cold northern winds and contributes to increased snow accumulation. Our research (May 5th 2019) showed that the height of the snow cover at the site was about 120 cm relative to 70 cm at the Norilsk meteorological observatory. Higher snow accumulation leads to later onset of thawing, the reason why we chose the sum of positive degree-days for the period after snow melt (see below).

METHODS, MATERIALS AND DATA

Field methods

The CALM site was established in 2005 near Talhakh (69^{o}26'N, 88^{o}28'E), a satellite city of Norilsk. The site is registered within CALM database as R32 «Talnakh» (www.gwu.edu/~calm). Data are available at the Arctic Data Center web site (https://arcticdata.io/catalog/view/doi:10.18739). Active layer thickness was measured on a 1 ha grid using mechanical probing with a metal probe (Brown et al. 2000; Fagan and Nelson 2017). The probe is a pointed metal rod with a cross section of 10 mm and a length of 1.6 m. Three measurements were made at each of the 121 equally spaced grid points (10 m spacing) at the end of August or beginning of September, from 2005 to 2020. The total number of measurements was approximately 6000 during this period.

Geodetic surveys for evaluation of thaw subsidence were conducted at the site in 2007. Geographic location and surface elevation were determined by theodolite surveys, relative to a fixed benchmark. Subsidence was

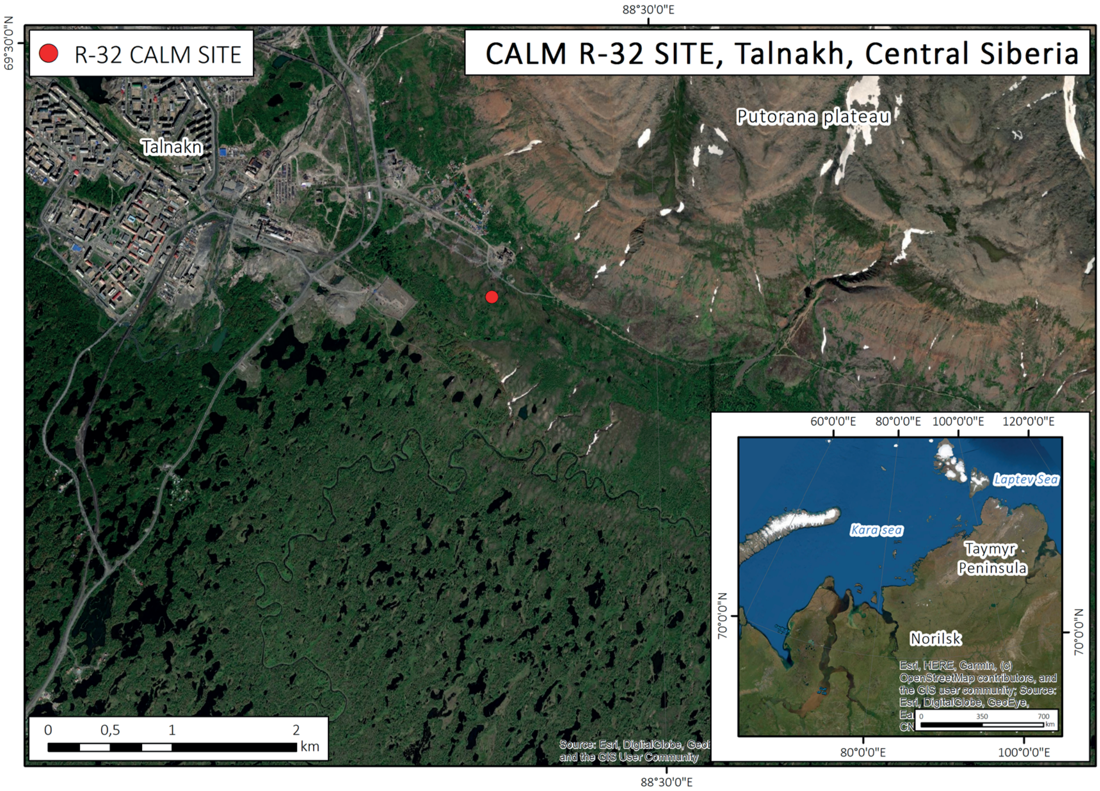

Fig. 1. Location of the R-32 site

estimated as the difference in elevation between the benchmark and the 121 marked points of the grid.

Landscape maps were compiled for 2005, 2008 and 2017. Geobotanical mapping of landscape complexes enabled assessment of transformations in the site's landscape structure, and guided the landscape-specific analysis of thaw values by landscape group. Landscape groups were delimited using several parameters, including microrelief (lower parts and higher parts based on the geodetic surveys of the site), surface hydrologic regime, and vegetation. Vegetation descriptions were conducted within the defined microrelief types, e.g., runoff hollow. The dominant vegetation type was recorded for the different levels.

Analytic procedures

Degree-days of thawing (DDT) were used for the analysis of the influence of warm-season air temperature on ALT. DDT is the sum of the positive average daily temperatures from the beginning of the warm period to the time of ALT measurement (Boyd 1973). In this study, the sum of positive temperatures from the date of snowmelt to the ALT measurement date was used.

Traditionally, a version of the Stefan Solution is used to compute ALT (General Permafrost Science 1967; Harlan and Nixon 1978). The latter was applied in the form of the equation $Z = E\sqrt{DDT}$, where E is the «edaphic factor», describing the thermal properties of the surface and thawing soils (Nelson and Outcalt 1987).

Meteorological data were obtained from the Norilsk Meteorological Observatory (WMO ID 23078), located 17 km southwest of the CALM grid, at the elevation of the Valkovskaya lacustrine-alluvial terrace.

The normalized variability index (I_v) was used to estimate the spatial variability of thaw over the time series following Brown et al. (2000) and Hinkel and Nelson (2003). Iv is determined by:

$$I_v = [(Z_i - Z_{avg}) / Z_{avg}] \quad (1)$$

where Z_{avg} is the average thaw depth for a specific year, and Zi is the value for a specific grid point. The variability for the 16-year series is calculated as the difference in the ratios (expressed as per cent) of the minimum and maximum achieved over these years. Some researchers have suggested classifying low variability when the Interannual Node Variability index INV = 0-19%; medium with INV = 20-29%; and 3) high - with INV> 30% (Smith et al. 2009).

The Pearson Product Moment Correlation method was used to assess changes in the micro-landscape structure of the site by the annual datasets (Gmurman 2010). We measured the strength and direction of the relationship between two variables using the nonparametric Spearman rank correlation coefficient. We conducted pointwise analysis between every single point from the 121-point dataset. We correlated every point from the dataset with its analogue from different years. The result is a matrix with the correlation between datasets from different years. Another important statistical parameter that we used is the coefficient of variation (2)

$$C_{v,} = \sigma / \bar{a} \quad (2)$$

where σ is the standard deviation and ā is the arithmetic mean of ALT values (Ivchenko, Medvedev 2010).

Maps were made using the Surfer software package (Surfer 1999), which facilitated creation, comparison, and analysis of the spatial distribution of ALT values at the site between the years following (Hinkel and Nelson, 2003; Kaverin et al. 2019).

Climate data

The territory is characterized by a polar tundra climate (Kottek et al. 2006), with polar nights and polar days, long snowy winters, and relatively short cool summers. According to meteorological data obtained at the Norilsk Meteorological Observatory, the average annual wind speed is 6.3 m / s; rainfall – 340 mm per year; the height of the snow cover is 80 cm.

Analysis of meteorological data from the Norilsk Hydrometeorological Observatory (1938-2020) shows that after a sufficiently long period of increased climate severity and its subsequent relative stabilization there is a pronounced warming trend since the 1960s (Fig. 2). The averaged MAAT was -9.8 0C, and the duration of the warm period was about 120 days in the 1970s (Handbook of Construction 1977); while in the 1988–2020 period mean annual temperature was -8.2 0C. The temperature in 2020 was -3.80C, which is 4.70 OC higher than the climatic norm (1981–2010). The season with positive daily air temperature lasted 150 days in 2020. There was an almost weeklong period with a temperature above 00C in mid-April, which contributed to early snowmelt.

An increase in air temperature with a slight increase in snow cover depth in the winters led to the growth of trees and shrubs, creating a transition to southern tundra (Nyland et al. 2017). Thermokarst processes on the Valkovskaya terrace, thermal erosion on river banks and ice-rich shores of large lakes were also more common. The number of deformed engineered works on frozen piles has significantly increased in the cities and industrial zones of the region. According to our observations (Grebenets et al. 2016) the reason was an increase in the permafrost temperature of the upper permafrost (8-10 m), and the subsequent decrease in the freezing forces on the foundations.

The region lies within the zone of continuous permafrost. Taliks underlie the largest rivers (Norilskaya and Rybnaya), and the largest lakes on the Valkovskaya terrace. Permafrost temperature decreases with elevation (Sheveleva and Khomichevskaya 1973).

Permafrost underlies the entire CALM site. The upper part of the permafrost section is dominated by loamy strata with a relatively small amount of gravel-pebble material. Loams have a thin layer of partially decomposed peat from the surface in some places. Mean annual ground temperature (MAGT) at the level of zero annual amplitude is -3.8 ° C. These data were acquired from the archives of the Research Institute of Foundations and Underground Structures, Norilsk.

RESULTS

Impact of climatic conditions on active layer dynamics

Sixteen years of observations show that ALT has an increasing trend of 1 cm / year (Fig. 3). Thawing rate depends primarily on the cumulative effect of DDT and the warming effect of precipitation in summer (Fig. 3).

Fig. 3 shows that average ALT at the site varies from 81 cm (2005) to 113 cm (2019). DDT varies from 794 (2010)

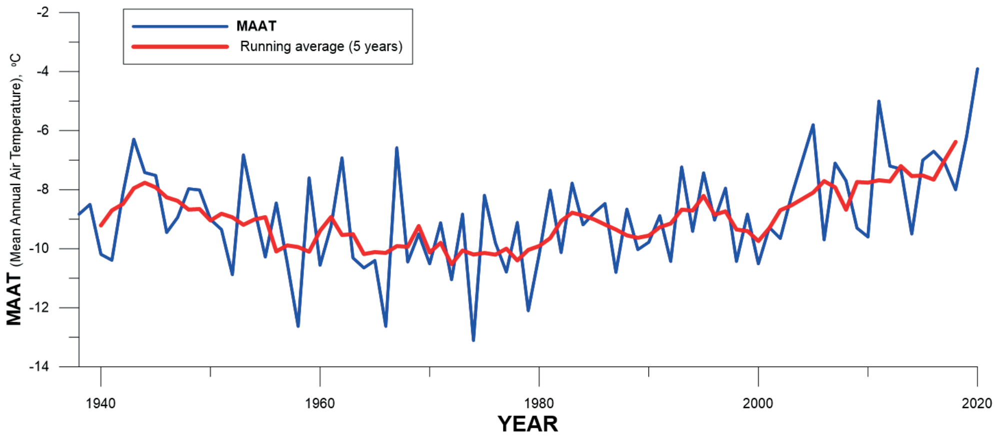

Fig. 2. Changes in mean annual air temperature in Norlilsk (data from the Norilsk Meteorological Observatory). Blue line represents mean annual air temperature (MAAT). Red line represents the 5-year running average

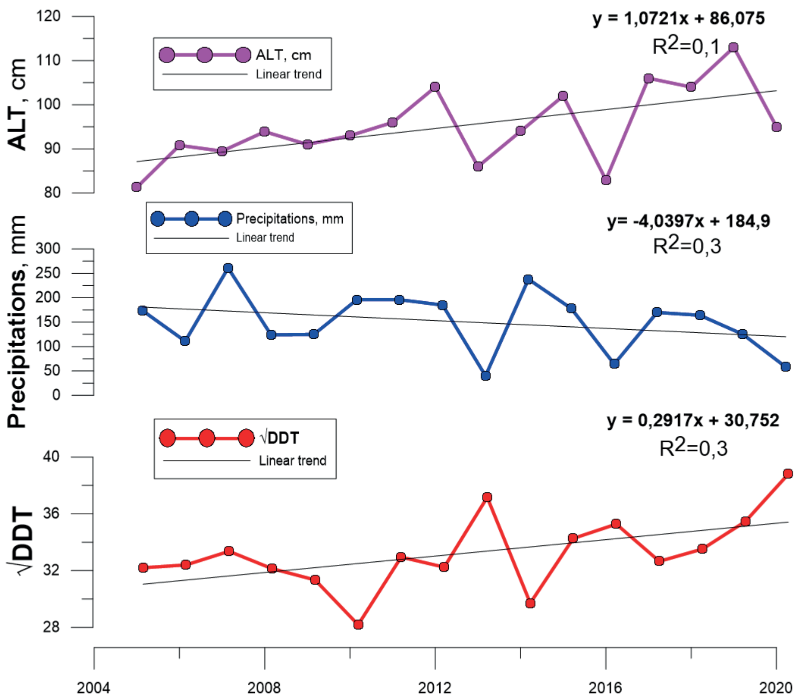

Fig. 3. Time series of active layer thickness, degree days of thawing, and precipitation for the 2005–2020 period

to 1506 degree-days, (2020). Most variable is the regime of summer precipitation: from 40 mm (2013) to 261 (2007) mm. Cv=0.4. (C_v for √DDT=0.1; for ALT=0.15) Average thaw depth over the last 16 years at the R-32 site is 96 cm. According to the generalized results of measurements in the loamy strata of the region until the 1980s, ALT was 80 cm.

Bivariate regression analysis revealed the absence of a linear dependence over 16 years only on DDT and the amount of precipitation (Fig. 4).

Figure 4 shows that in both cases the coefficient R^2 was less than 0.1 Active layer thickness did not exceed the long-term mean values (95, 86, 83 cm) in dry years, even with extremely hot summers and maximum values of positive degree days (2020 – 1506, 2013 – 1381, 2016 – 1244).

A clearer dependence of ALT on DDT is manifested if we group the measurement results (average values for the site) by years with warm and humid conditions (Fig. 5, a) and a relatively dry summer (Fig. 5, b). The relationship between soil thawing and air temperature is quite strong for the first case, with R^2 value of 0.7.

Higher than average ALT was reached in 2012, 2015, 2017, 2018, and 2019, when the amount of precipitation was higher than or near the mean annual values. More than half (56%- 103 mm) of precipitation fell in the second half of July, at the beginning of August in 2012, with very high average (for this period) air temperature of 15.8°C (this value is higher than the average annual temperature values at that time). These conditions resulted in a well-developed active layer of 104 cm. A total of 179 mm of precipitation fell in 2017. This is 1.14 times greater than the average for the season. The bulk of precipitation fell in July and August (61 and 103 mm); the soil had thawed to a sufficient depth by this time that downward water drainage activated thaw.

The summer of 2018 was abnormally warm in June (13.8° C, which is 3.8 ° C higher than the average value for the 16 years of this research project). A total of 66 mm of precipitation fell during this period (1.53 times higher than the average value for this month). Consequently, a thick active layer formed during the cold remaining months (72 and 44 mm of precipitation). The increase in ALT was most pronounced in August of 2019, when the average air temperature was 4.6°C higher than the mean temperature for this month for the period 2005–2021. The month was very rainy (72 mm of precipitation) leading to record for seasonal thaw (113 cm). The influence of the combination of high DDT and high precipitation on the active layer thickness is significantly «corrected». The first correction is the shift of the maximum air temperature late in the warm season. The second is the regime of summer precipitation: at the beginning of the warm season when most of the precipitation drains atop the frozen soils near the surface, or drains along the peat loam in the upper part of the section. The maximum impact on ALT from these positions is recorded during rainy Augusts.

Table 1 shows the results of measurements that emphasize the peculiarities of the influence of the number of positive degree-days in combination with the amount of precipitation in the warm period.

An interesting pattern occurred in years with abnormally hot and dry summers (2013, 2016, and 2020). Only 40 mm of precipitation fell over the summer of 2013, (ALT 86 cm) and only 4 mm of precipitation fell in July 2016 (ALT 83 cm) at an average monthly temperature of 18 ° C. The total amount for the 2016 warm season was 64 mm. ALT was only 95 cm in dry 2020 (precipitation of 58 mm), with an early snowmelt (April 24). The date of transition to positive air temperatures was also abnormally early (May 8th). The amount of DDT was maximal (1506 degree-days).

The formation of the seasonally thawed layer at the site cannot always be explained by the cumulative effects of only heat and moisture. One of the lowest values of ALT was observed in 2007 with greater than average precipitation and DDT. Similar results have been obtained by other researchers (Maslakov et al. 2019).

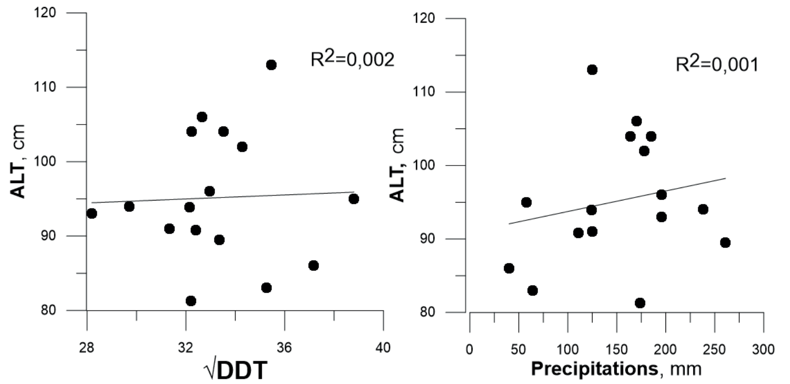

Fig. 4. Dependence of thawing depth on two main factors: the root of positive degree days (a) and summer precipitation (b)

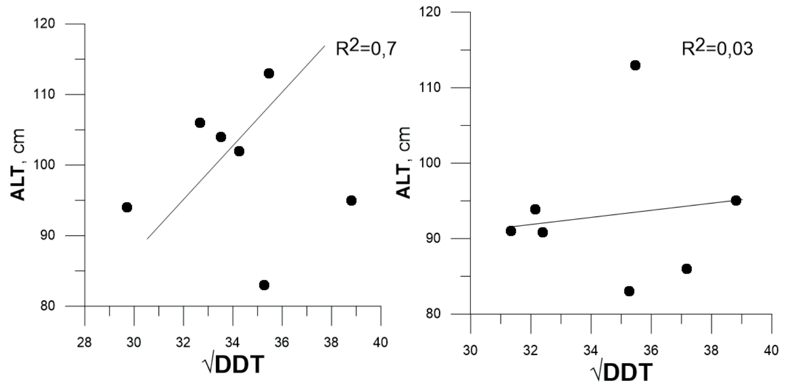

Fig. 5. Dependence of ALT on positive values of air temperature in (a) relatively dry and (b) more humid summer periods

Table 1. The main parameters of active layer and weather conditions affecting its formation

Year	DDT	Precipitations, mm (May-August)	Mean ALT, cm	Cv	INV, min %	INV, max,%
2005	1037	174	81	23.4	-40	84
2006	1050	111	90	24.7	-53	56
2007	1113	261	90	22.2	-45	57
2008	1033	124	94	22.5	-42	58
2009	982	125	92	21.4	-44	57
2010	795	196	93	26.9	-54	71
2011	1086	196	96	23.4	-47	67
2012	1040	185	104	23.0	-43	54
2013	1381	40	**86**	15.4	-100	34
2014	882	238	94	21.2	-44	80
2015	1174	178	102	20.5	-38	43
2016	1244	64	83	20.0	-42	41
2017	1066	170	106	23.8	-39	51
2018	1124	164	104	24.2	-35	54
2019	1258	125	113	19.7	-40	41
2020	1506	58	**95**	18.8	-45	67
Average	1111	150	95	21.9	-47	57

Very high variability in ALT was observed at the site. The interannual variability is 184% in comparison with the average value over 16 years, which is extremely high (Table 1). This result is due to the large differentiation of the site in terms of microrelief, vegetation conditions, and thickness of the peat causing different rates of infiltration, transpiration, and other influential processes.

The coefficient of variation of ALT and the amount of precipitation in the summer period are very high (Fig. 6). The values of the coefficient are minimal in relatively dry summer periods. This indicates that the values of the ALT are grouped near average values. The coefficient is much higher for wet summers. They are more differentiated and grouped around the minimums / maximums in wet years. This is explained by the redistribution of moisture over the site, which leads to higher differentiation of soil thawing.

The annual contrasts of ALT are clearly visible in the maps showing ALT from 2005 to 2020 (Fig. 7). The difference between individual measurement points reach factors of 3–4 in some cases. The contrast in local conditions of heat transfer through the surface lead to this variability.

The R-32 site has a slight southward slope (Fig. 8), which allows water to move to the lower (southeast) part of the site or to stagnate in microtopographic depressions. Two runoff hollows (Fig. 8) redistribute water through the site. ALT values are higher than average in these types of landscapes. The second zone with the highest values of thawing is characteristic of the small well-drained areas occupied by bushes and trees (Alnus Fruticosa, Larex Sibirica and Betula Nana). This is due to the almost complete absence of moss and peat cover, the presence of roots, and increased pathways for summer precipitation through these more porous soils to lower areas.

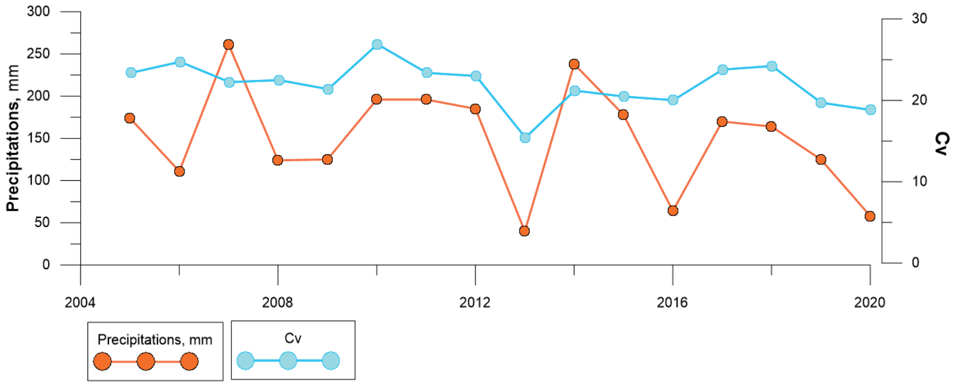

Fig. 6. Graph of the coefficient of variation (standard deviation of indicators for all points from the average value for a particular year) and the amount of summer precipitation

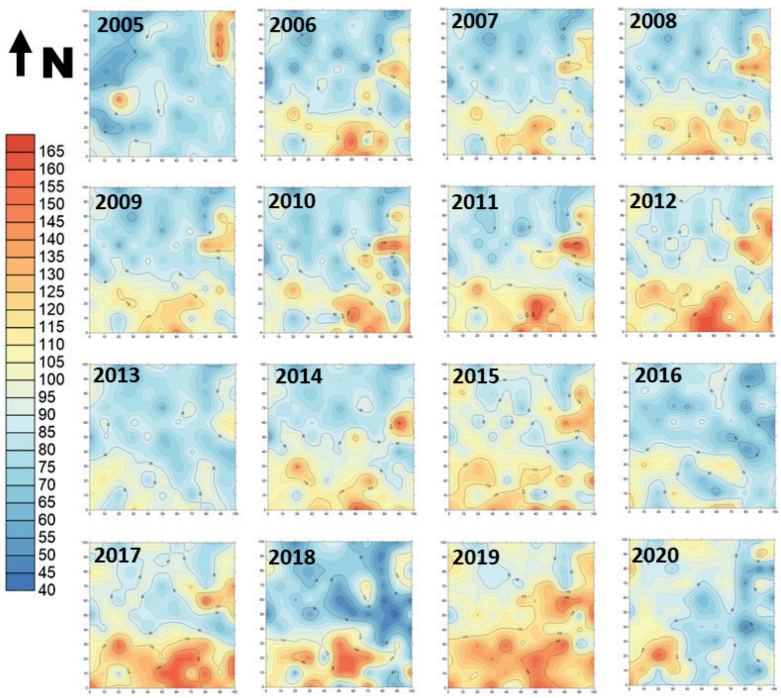

Fig. 7. Active layer thickness maps from 2005 to 2020

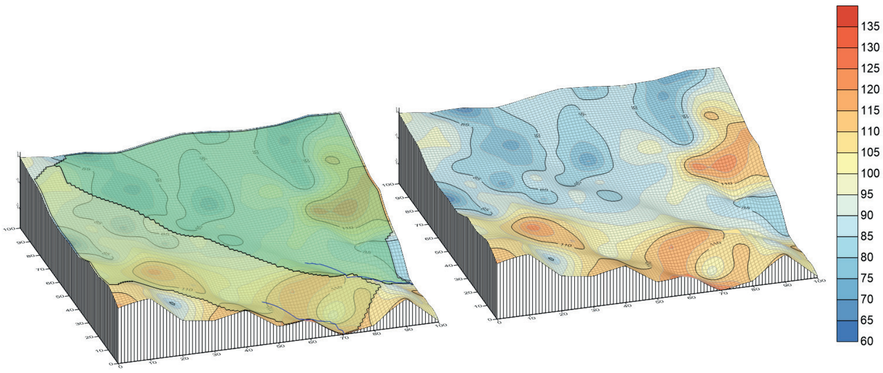

Fig. 8. The microrelief of the site R – 32 with (a) potential water tracks and (b) the average ALT map (2005–2020)

Microlandscape Control Over ALT

The moisture content of the soil affects the depth of thaw. Observations of microlandscape conditions over 12 years show that shrubs are growing rapidly in the eastern and southern parts of the site, which could enhance transpiration and decrease the water content of the active layer. The substrate base remains an inert system. Significant changes have taken place in the microlandscape environment. The height of the shrubs has noticeably increased in the southeastern part of the site compared to 2005. Differences in surficial water content have also increased. We observed, for example, formation of a new water track in the weak runoff hollow. This part of the site tends to be wetter than it was before during the previous decade of the research Water has stayed in this feature during the last 3-4 years of probing. The processes of uneven cryogenic heaving became noticeably more active in the southwestern part of the site (frost-boils on tundra).

The results from Spearman's correlation analysis confirmed that restructuring of the landscape is occurring in the site (Fig. 9).

The 121-point annual datasets were correlated between each other. Thaw values at specific points («thaw patterns») were similar and had a fairly high degree of correlation ($r > 0.75$) between the different years in the period from 2005 to 2010. All landscape-restructuring processes, such as growth of shrubs, the new small water track, and activation of spot medallions (frost boils), altered heat transfer through the surface. This demonstrates that patterns of ALT within the sites were substantially altered over the past decade. Correlation between the datasets for the last five years (2015 to 2020) is quite low and does not exceed 0.4 in general. The changed landscape conditions are shown in Fig. 10 and presented in Table 2. General changes include: the shrubs Salix pulchra and Betula nana have been vigorously expanded into a typical tundra community, consisting of Vaccinium vitis, Vaccinium uliginosum, Carex, Sphagnum for the last decade; the height and coverage area of shrubs and trees are noticeably increased due to growth of Alnus fruticosa and Larix sibirica.

The highest values of soil thawing are noted in those places where microrelief features contribute to thawing, for example, the lowest parts of the site containing stagnant water.

Additional research conducted in 2011 showed that thaw values vary significantly in different parts of frost boils. A large variability in thawing was recorded between the center of medallion spots with an open ground surface, a ridge with a dwarf-sedge-moss cover and a crack with a moist sedge-moss cover for 12 fresh medallion spots. The average depths in these features were 104, 87, and 91 cm. We compared microlandscape differentiation in the four types of microlandscape that contrast most strongly in terms of heat transfer through the surface:

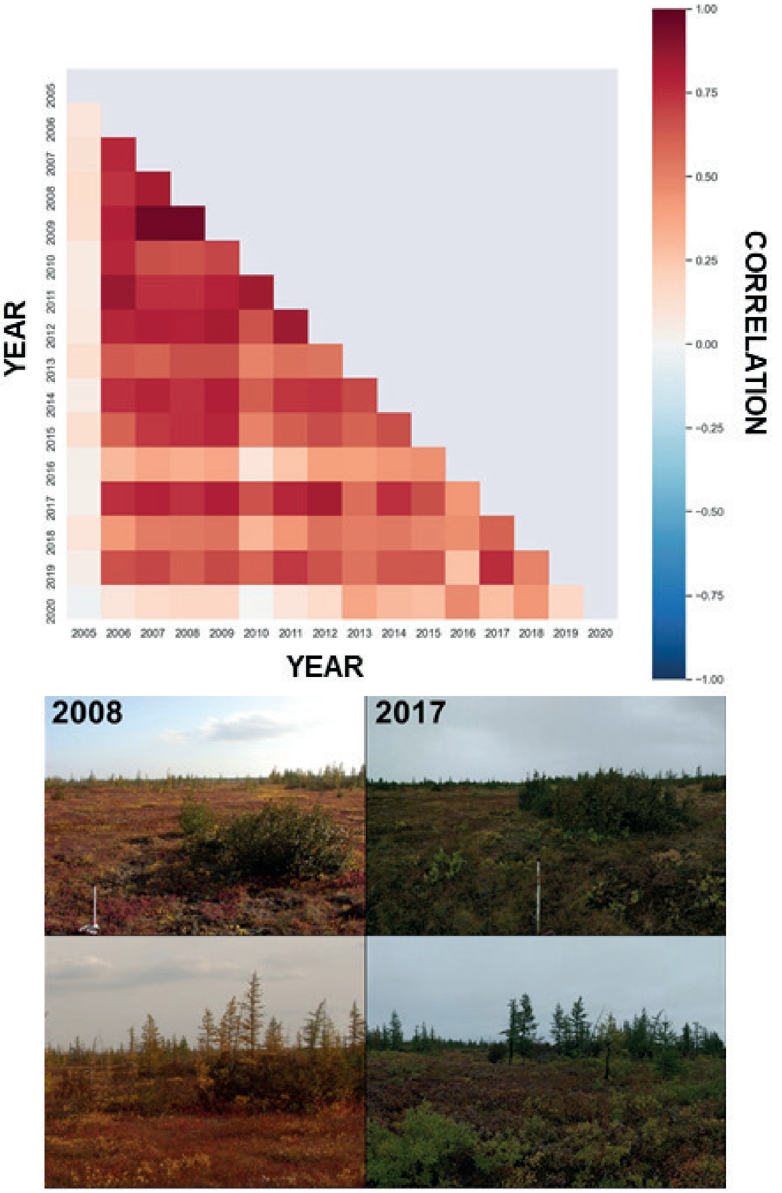

Fig. 9. Results from correlation analysis between the series of active layer thickness data (121 points) for different years. Each cell of the matrix represents the correlation value between two datasets from different years. The bottom part of the figure shows the expansion of bushes at the site. Photos are taken the first point and from the middle of the grid for the period 2008–2017

Table 2. Main landscape types at the site

Landscape type	Vegetation type
High and well-drained areas, with expanding shrubs, which contributed transpiration and decrease in active layer moisture	Larix sibirica, height up to 4-5 m Alnus fruticosa, height up to 2.5-3 m. Betula nana – up to 40-50 cm, Seldom – Salix pulchra, Exus, Vaccinium uliginosum, Vacinium Vitis), seldom -Carex
Frost boils on tundra with fresh frost boils (round loamy soil spots), with predominant sizes about 80-100 cm, the diameter of individual spots reaches 1,5 m, cracks between spots reach 20-30 cm in width and 10-15 depth.	Betula nana 40-50 cm, Ledum palustrum, Vaccinium uliginosum, Vacinium Vitis, seldom Carex, Sphagnum, lichen Cetraria islandica
Relatively flat, slightly swampy surface occupied by birch shrubs, hummocky-hillock surface, chaotic arrangement of hillocks and hummocks, the size of hollows does not exceed 30-40 cm	Betula nana, Salix Polarica, Vaccinium uliginosum, Carex, Sphagnum
Growing runoff hollows, going through all the site. Runoff hollows are most wet and low landscape type.	Salix pulchra, Betula nana, Vaccinium uliginosum, Rubus chamaemorus, Carex, Ereophorum vaginatum, Sphagnum
Downstream swamp, in the place of an overgrown thermokarst lake	Carex, Ereophorum vaginatum, Sphagnum
Thermokarst lake	

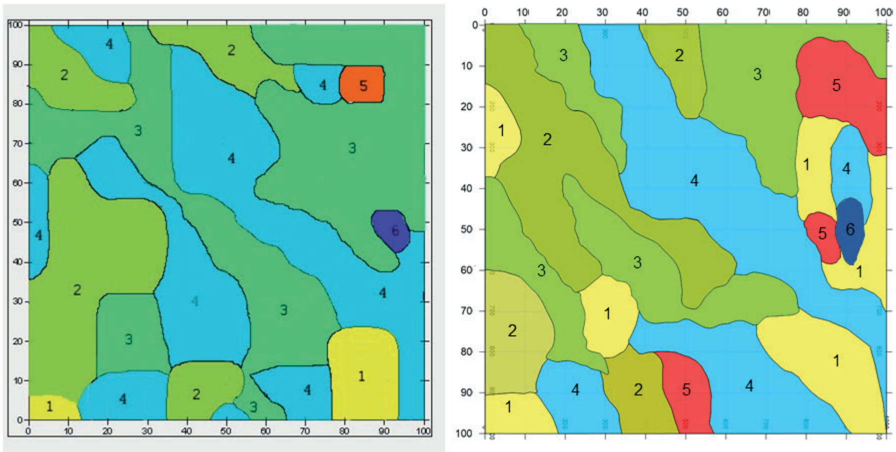

Fig. 10. Active layer thickness maps from 2005 to 2020

a) hummocky tundra with a dense and relatively thick moss-peat cover and shrub vegetation; b) runoff hollows with vegetation represented by sedge-moss communities with separate, low Salix pulchra bushes that have appeared in recent years; c) areas occupied by frost boils on tundra with minimal amounts of moss-peat cover; and d) hillocks with relatively high tree and shrub vegetation. Fig. 11 reflects the differentiation of ALT by landscapes for the observation period (from 2005 to 2020).

The highest values of thawing were found in waterlogged depressions between positive microforms of the relief, and in areas with frost-boils or well drained relatively elevated areas. ALT is lower (much less susceptible to weather fluctuations in different years) within the hummocky tundra occupied by shrub-sedge-moss communities. Moss is a good thermal insulator and provides a relatively uniform heat supply and moisture to soils.

Thaw subsidence

Geodetic surveys of surface elevation were performed at the end of the thawing period, relative to the first point. Because measurements of the surface level at the beginning of the thawing season were not conducted at the site, it is possible to monitor only relative interannual subsidence. Data on intra-annual surface changes, including heaving and subsidence organised at another CALM sites in the Russian northwest and Alaska's North Slope show the importance of thaw subsidence monitoring (Mazhitova and Kaverin, 2007; Shiklomanov et al. 2013; Streletskiy et al. 2017).

Surface elevation remains relatively stable, but it is apparent that the lower, wet areas with a sufficient amount of snow accumulation experience more active subsidence. Analysis of the thaw subsidence rate in various types of landscapes showed that the most stable type of landscapes are areas with well-developed moss cover. Thaw depth here is also minimal. (Table 3). The maximum subsidence rate was found in runoff hollows and open areas of the frost-boil tundra.

There is a very slight difference in surface changes in different years. The thaw subsidence rate does not always directly follow the value of the ALT.

The minimum ALT over 16 years of observations occurred in 2013. The thaw subsidence rate in that year, however, was close or greater than the average in 2013. This is attributed to excessive precipitation in the previous

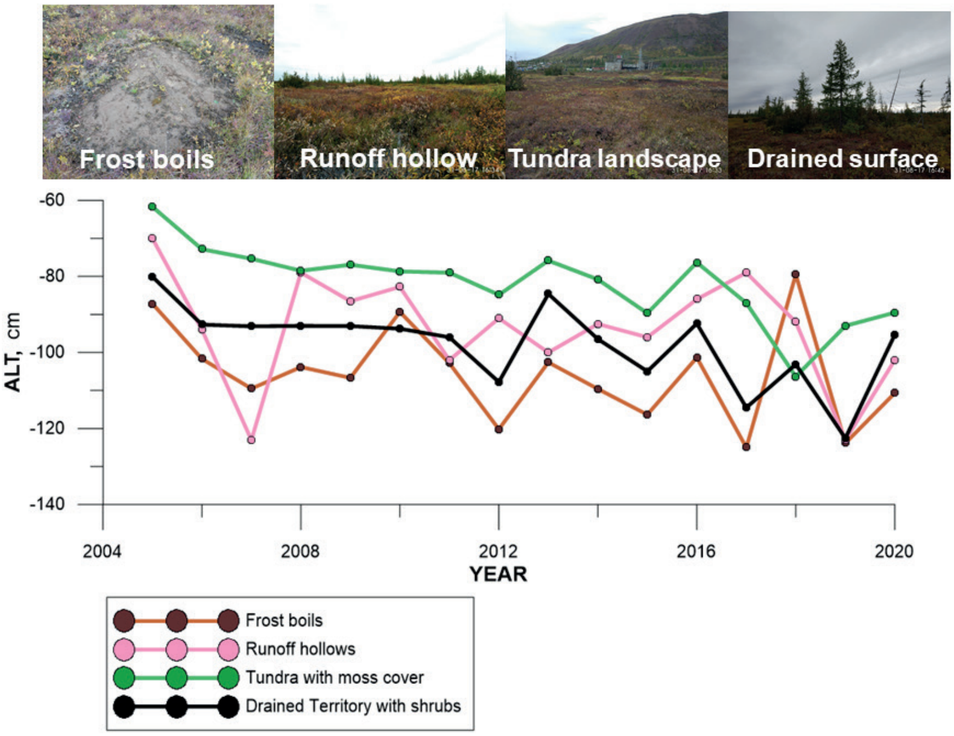

Fig. 11. Active layer thicknesses in different landscape types

Table 3. Thaw subsidence rates in different landscapes

Year	Frost Boil	Frost Boil	Tundra	Tundra	Runoff Hollow	Runoff Hollow
	Geodetic changes, cm	ALT	Geodetic changes, cm	ALT	Geodetic changes, cm	ALT
2010	-3	112	0	84	-4	101
2011	3	110	0	90	16	108
2012	-3	113	1	105	6	121
2013	0	76	-1	84	-21	84
2015	-1	94	-1	101	-4	98
2016	-1	76	0	82	4	79
2017	2	116	0	105	0	123
2018	-1	105	0	101	0	121
2019	2	125	0	101	0	121
2020	-4	92	0	96	-5	96
Total.subsidence	-4		-3		-8	

autumn (2012). The active layer had the maximum moisture saturation, leading to formation of segregation ice. Summer melt of a large amount of ice in the active layer increased the surface settlement. The precipitation regime also played an important role in warm seasons. Heavy rains occur after snowmelt and during the first period of thawing moisten the soil. Water has low compressibility in its liquid state and ice-rich permafrost has low infiltration capacity. These factors lead to the water-stagnant regime of the active layer, protecting it from thaw subsidence. It called «weighing» action of water (SP 25.13330.2012).

The northern part of the site is more stable (relative to point 1). The southwestern part contains more wet soils at the end of the warm period. The latter area recorded a wide range of changes in the soil surface due to higher ice content and the existence of the runoff hollows as water tracks here. Surface «breathing» affects the regimes of floods in each of the specific summer period. These factors can cause local («point») places of desiccation or stagnancy of the soil.

DISCUSSION

Additional work will be required to identify other factors affecting the formation of the active layer at this site. In particular, information about changes in soil moisture and temperature, pre-winter moisture and ice content of frozen soil, the number of frosts during the warm season will be needed. Some researchers state that ALT can be forecast with a sufficient degree of accuracy for most purposes (Bonnaventure and Lamoureux 2013). This does not work for all monitoring sites. Field-based studies (Kaverin et al. 2019) have shown that estimated and forecast ALT, based only on analysis of the sums of positive air temperatures, are not sufficient for soils with different peat content. This conclusion also applies to the Talnakh research site.

The heterogeneity of heat transfer results from soil type and vegetation cover, the thickness and duration of snow cover in certain areas, differences in the ice content of the frozen soils, the porosity of thawing soils and presence of peat formation, temperature regime and the micro-relief of the study area (Nelson et al. 1998; Kaverin 2014, 2019). These factors affect the depth of the active layer.

The depth of thaw based on the results of field observations at the R-32 (Talnakh) site depends on the amount of heat transferred to the soil surface. It includes the multiple factors discussed above, including air temperatures and rain. A combination of these meteorological parameters in certain years («warm – humid», «warm – dry», etc.) and its details during the summer period peaks of temperature increase and precipitation (coincidence / non-coincidence of the rainiest and the warmest periods, and a shift of the maximums of these weather characteristics by the end of July – August, when the thawing is already deep enough) are responsible for the formation of active layer.

Record values of active layer thickness were observed in 2012. These could affect the icy transition layer. During the subsequent heat wave in 2013 accelerated growth of shrubs and landscape restructuring of the site occurred. Differentiation of landscapes within the site is quite noticeable in recent years. This is very apparent in the photos of Fig. 9. These changes determine different conditions of heat transfer, which are enhanced by the dissection of the relief caused by topoclimatic and geomorphic processes.

One of the features of the site is the presence of patches of frost boils on tundra. The processes leading to their formation have been observed during some years (e.g., 2018). According to our hypothesis, its intensification is associated with high pre-winter humidity in some years and low values of negative temperatures in November – December, when the active layer is nearly completely frozen. The activation of the processes of frost boil formation in the southwestern part of the site is associated with the destruction of the soil and vegetation cover, the protective role of which is well known. It significantly affects ALT values.

CONCLUSIONS

A decrease in the severity of the climatic conditions in Taimyr has contributed to major changes in the natural and anthropogenic systems (Kirdyanov et al. 2012; Nyland et al. 2017; Grebenets et al. 2016). These changes are growth of shrubs and trees, an increase in moss and peat cover; increases in the occurrences of building deformations, rising permafrost temperatures, and decreases in the bearing capacity of piles. Field measurements of the parameters of the active layer conducted within the framework of the CALM program at the R-32 (Talnakh) site, showed that over the past 16 years, there has been a tendency towards an increase in the thaw depth of 1 cm / year.

The depth of thawing and the number of positive degree-days illustrates that ambiguity can exist in the relationship between these two parameters. There was no statistical relationship found between the amount of summer heat expressed as degree-days of thawing and active layer thickness. This is associated with the extremely high variability of the amount of atmospheric precipitation during the warm period, with variability in precipitation from year to year reaching up to six times. Statistical analysis shows that the dependence of thaw depth on DDT can be improved if summers with a similar amount of precipitation are compared, underscoring the importance of precipitation on active layer dynamics. The seasonal thaw of soils will be higher if the peak in precipitation shifts from June to the second half of July and August, when the underground runoff in soil is limited and precipitation penetrates deeper and enhances thawing.

Changes in landscape structure were detected at the site during the 16-year observation period, associated particularly with active growth of shrubs and trees. Polar willow has spread quite widely, occupying places that were not previously covered by this species. The maximum seasonal thawing of soils is recorded in runoff hollows, relatively elevated and well-drained areas with trees and shrubs, and in the centres of frost boils. These types of landscape occupy about half of the site. The diversity in vegetation and large differences in the thickness of the moss-peat cover has led to a significant difference in ALT in different years. Interannual differences can involve factors of two or three.

Thaw subsidence rate has a relative relationship with the depth of thawing. The properties of soils have a noticeable effect on thaw values. Local conditions of drainage and surface runoff, types of vegetation, and soil characteristics play important roles in thaw subsidence rate.

The study of active layer dynamics in Taimyr is important, as the region is relatively lacking in permafrost observations and is one of the areas being affected by pronounced climatic warming and the presence of a substantial human population and extensive infrastructure built in permafrost terrain.

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