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Long-term active layer monitoring at CALM sites in the Russian European North

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ABSTRACT
This paper presents results from long-term active layer monitoring at four CALM sites in the Russian European North. Observational records range from 10 to 24 years in length (1996–2019). The impact of climatic and landscape parameters on active layer thickness has been assessed through linear regression. The temporal dynamics of climatic parameters, responsible for the thaw depth changes, were investigated. The long-term data indicate that the active-layer thickness has increased at all the monitoring sites, in response to changes in both summer and winter climatic parameters. The surface organic layer also serves as a major landscape factor influencing spatial patterns of thaw depth and climate-induced rates of permafrost thawing.

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Active layer thickness; climate change; permafrost; monitoring

Introduction

The Russian European Northeast is characterized by the widespread distribution of the relatively warm and unstable permafrost (−2 … −0 °C), highly sensitive to long-term air temperature fluctuations (Malkova et al., 2011). During the early part of the twenty-first century, a distinct increasing trend in regional air temperature has led to intensive permafrost thaw throughout the Russian European North (Oberman & Shesler, 2009). The theory of 50-year climatic cycles suggests the existence of alternating 25–year cold and 25–year warm periods where the climatic cycle, starting in 1995, is a cooling phase (Pavlov, 1997; Oberman & Mazhitova, 2001). However, observations indicate that climatic warming has persisted through the 1990s and 2000s and has promoted the thaw of perennially frozen ground (Mazhitova & Kaverin, 2007).

The Circumpolar-Active-Layer-Monitoring (CALM) program was designed to observe the response of the active layer and near-surface permafrost to climatic variability and change (Brown et al., 2000; Shiklomanov et al., 2008). Four CALM sites were established in the continuous and discontinuous permafrost zones of the

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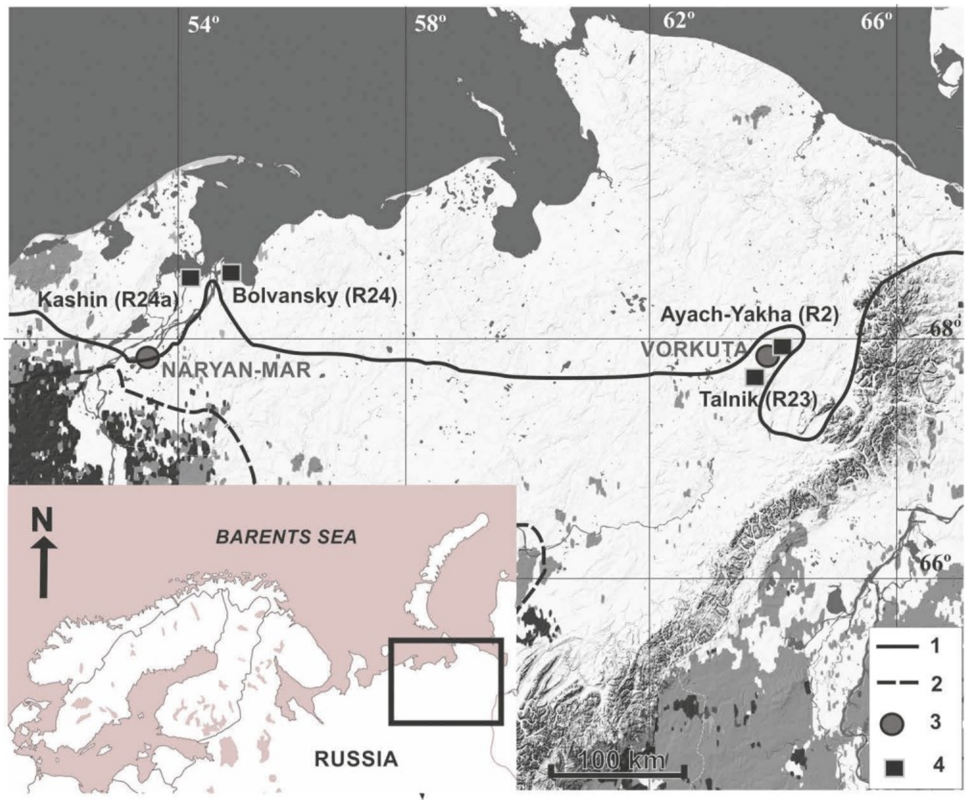

Figure 1. Location map of the European Russian CALM grids. 1) boundary between continuous and discontinuous permafrost zones 2) southern boundary of cryolithozone 3) settlements 4) CALM-sites

Russian European North over the 1996–2010 period (Figure 1). This paper discusses the long-term (1996–2019) observed temporal trends of the active-layer thickness (ALT) in relation to the variability of the atmospheric and landscape-specific edaphic factors.

Study areas

Active layer trends observed at four CALM sites characteristic of the Russian European North are considered for analysis. Within the CALM program, the designation of sites consists of an alfa-numerical code where the letter represents the country ('R' for Russian Federation) followed by the numerical order of a site. Sites with a lower number usually have a longer observational record. The letter following the number indicates the different landscape characteristics of nearby sites. Within the Russian European North four sites differ in climatic conditions, landscape characteristics and, as a result, have different depths of annual thaw propagation. Each site consists of regular 100 × 100 m grids with 10 m intervals between grid nodes. All grid nodes are marked with wooden stakes.

Two sites, Ayach-Yakha (R2) and Talnik (R23) are located in the eastern part of the Russian European North, and the other two sites, Bolvansky (R24) and Kashin Island (R24A) are in the central part of the region.. The sites R2 (established in 1996) and R23 (established in 1998) are representative of the Cis-Ural depression located on the West Piedmont Plain of the Polar Ural Mountains, while the sites R24 (established in 1999) and R24a (established in 2010) are located in the lower Pechora River region (Figure 1). The study area is characterized by relatively warm continuous permafrost with closed taliks present in portions of the Talnik (R23) and Bolvansky (R24) sites. The taliks were formed as a result of permafrost table retreat in depressions. Climate data from the Russian Hydrometeorological Service (Federal Service, n.d.) was used for the analysis. Long-term climate observations are available from two meteorological stations located in the towns of Naryan-Mar (eastern part of the region) and Vorkuta (central part of the region) (Figure 1). Site-specific descriptions are provided below.

Bolvansky (R24) site. The site is located on the Pechora River Delta in the northernmost part of Cape Bolvansky (Figure 1). The Cape consists of an undulating plain with numerous lake basins and large flat-bottomed valleys. Elevation varies from 26 to 31 m.a.s.l. The surface deposits consist of boulder sandy loams, peat layer thickness varies from 0.5 to 5 m.. The area is located at the western extremity of the continuous permafrost zone. Near-surface permafrost occurs under convex and flat areas, and the permafrost table is much deeper (closed taliks) in valleys. A closed talik is located at the southeastern corner of the site. R24 site occupies a hilltop with gentle slopes. The surface elevation ranges 5 m within the site. It is covered with dwarf shrub/lichen vegetation and numerous frost boils. Soils are classified as Reductaquic Cryosols and Gelic Stagnosols. The mean annual ground temperature (MAGT) at the depth of zero annual amplitude (10 m) was about −1.5 °C in 2016. The ground temperature within the active layer ranged from-1.8 to 1.5 ° C over the 2006–2019 period (Figure 4). Soil volumetric water content varies from 21 to 59%. The highest soil moisture values are associated with a waterlogged depression associated with the talik. Snow cover depth varies from 0.50–0.80 m in different years, and the average value for 30 years is 0.65 m. The peat horizon is 0.05 m thick on average throughout the site. The height of the shrubs ranges from 0.5 to 1.1 cm.

Kashin Island (R24a) site. The site is located on the first marine terrace, 50 km of the R24 site (Figure 1). The island surface is complex and includes partially drained lake basins and localized depressions occupied by bogs and tall willow stands. Elevation varies from 2 to 12 m a.s.l. Organic layer thickness varies from 0 to 0.25 m, averaging around 0.13 m. Soils are classified as Gelic Stagnosols and Histic Cryosols. Soil parental sediments are dominated by fine sands, underlain by loams at 4–6 m depth. The depth of the permafrost table varies from 0.30 to 1.00 m, descending to several meters beneath fens and willow stands.

According to data from the Naryan-Mar meteorological station, located approximately 94 km north-northeast from R24 and R24a sites, the 1960–2019 average Mean Annual Air Temperature (MAAT) is −3.2 °C (Figures 2 and 3). The 1960–2019 average sum of annual precipitation is 475 mm (Figure 3).

Ayach-Yakha (R2) site. The Ayach-Yakha (R2) CALM site is located 13 km northwest of Vorkuta (Figure 1). The site is located on an undulating plain covered with glacial-marine silty loam. The thickness of local Quaternary deposits varies from 1.0 m to a few dozen meters, they are underlain by bedrock. The site occupies a gentle southwest-facing slope with elevation ranging approximately 5 m. Soils are classified as Turbic Histic Cryosols. MAGT at the depth of zero annual amplitude (10 m) in the Vorkuta area varies between −0.1 and −2.0 °C (Oberman & Shesler, 2009). The upper permafrost layer at the site is characterized by rather 'warm' negative temperatures in the range of −0.1 to −1.0 °C.

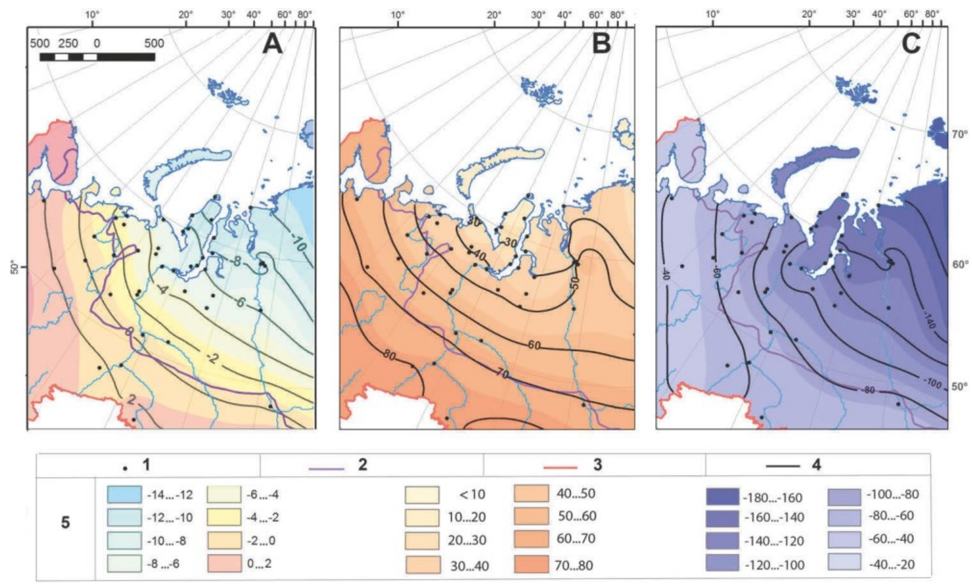

Figure 2. Comparison of regional climate parameters for the 1960–1990 (color patterns) and 2000–2015 (isolines) periods: MAAT, °C (A); thaw index (TI), °C – months (B); freezing index (FI), °C – months (C); meteorological stations (1), southern limit of the cryolithozone (2), border of the Russian Federation (3), climate isolines in 2000–2015 (4), color scale of climate parameters in 1960–1990 (5)

The ground temperature within the active layer ranges from −3.5 to +3.0 °C (Figure 4). Site-averaged volumetric water content in the upper soil horizons varied from 35 to 62% over the 1999–2019 period. Site-averaged end-of-March snow thickness ranged from 0.30 to 0.88 m over the 1999–2019 period. The organic layer thickness varies between 0.04 and 0.20 m across the site, averaging 0.12 m. The height of the shrub layer is from 0.5 to 0.6 m.

Talnik (R23) site. This site is located 20 km south of the town of Vorkuta (Figure 1) on the same undulating glacial-marine plain as the R2 site. It occupies the gentle northeast-facing slope of a loamy ridge. The range of relative elevations is 4.7 m, where half of the site is occupied by the ridge and the rest by a depression. About 56% of the site's area is covered with lichen-moss-willow vegetation, and the rest by feather mosses (*hylocomium splendens*) and dwarf birch (*Betula nana*) communities. In depressions, willows are up to 1.5 m high. Soils are classified as Gelic Stagnosols and Histic Cryosols. Site-averaged volumetric water content in the upper soil horizons ranges spatially from 22 to 81%. The organic horizon is relatively thin, varying from 0.01 to 0.37 m, with a site-averaged value 0.17 m. Snow thickness reaches 2.0 m in depressions and ranges from 0.40 to 0.60 m on the ridge. Permafrost is discontinuous, and up to 20 m thick. MAGT at 10 m depth is −0.1°C (Karelin & Zamolodchikov, 2008).

The 1960–2019 average Mean Annual Air Temperature as observed at the nearby Vorkuta weather station is −5.4 °C and the 1960–2019 average annual precipitations are 542 mm (Figure 3).

Methods

CALM sites in European Russia employ the standard systematic sampling design recommended by the observational protocol of the CALM program (Brown et al., 2000;

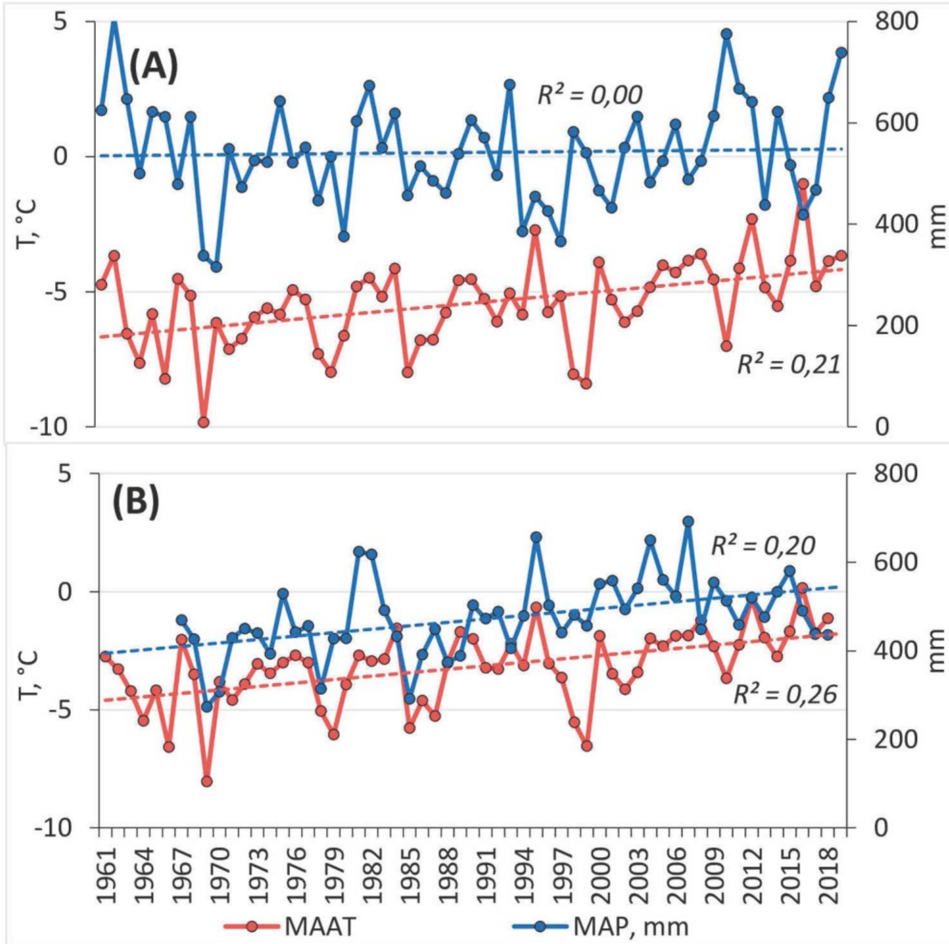

Figure 3. Dynamics of Mean annual air temperatures (MAAT) and Mean annual precipitation (MAP) at CALM sites according to Vorkuta (A) and Naryan-Mar (B) weather stations.

Fagan & Nelson, 2017). The active-layer thickness is inferred from the thaw depth measured annually at approximately the same date in September, which corresponds to the end of the ground thawing season. The measurements are done by inserting a graduated steel rod into the ground to the point of resistance. Thaw depth observations are conducted at each grid node providing a 121-point sample for each site annually.

Annual site-specific values of the active-layer thickness (ALT) were calculated by averaging the 121 measurements conducted at individual grid nodes. Temporal trends in annual ALT over the site-specific observational periods were calculated through linear regression, where measurement years served as the independent variable (x) and thaw depth as the dependent variable (y). Coefficients of variation for annual ALT values were calculated as the ratio of standard deviation (s) to mean (μ) of grid-node ALT values. All statistical analysis was performed using Statistica 6.0 software (Statsoft team, 2001). Spatial interpolations of active layer thickness data obtained at each grid node were performed using Delaunay triangulation with linear interpolation using Surfer Spatial analysis software package (Golden Software, 2002/2005).

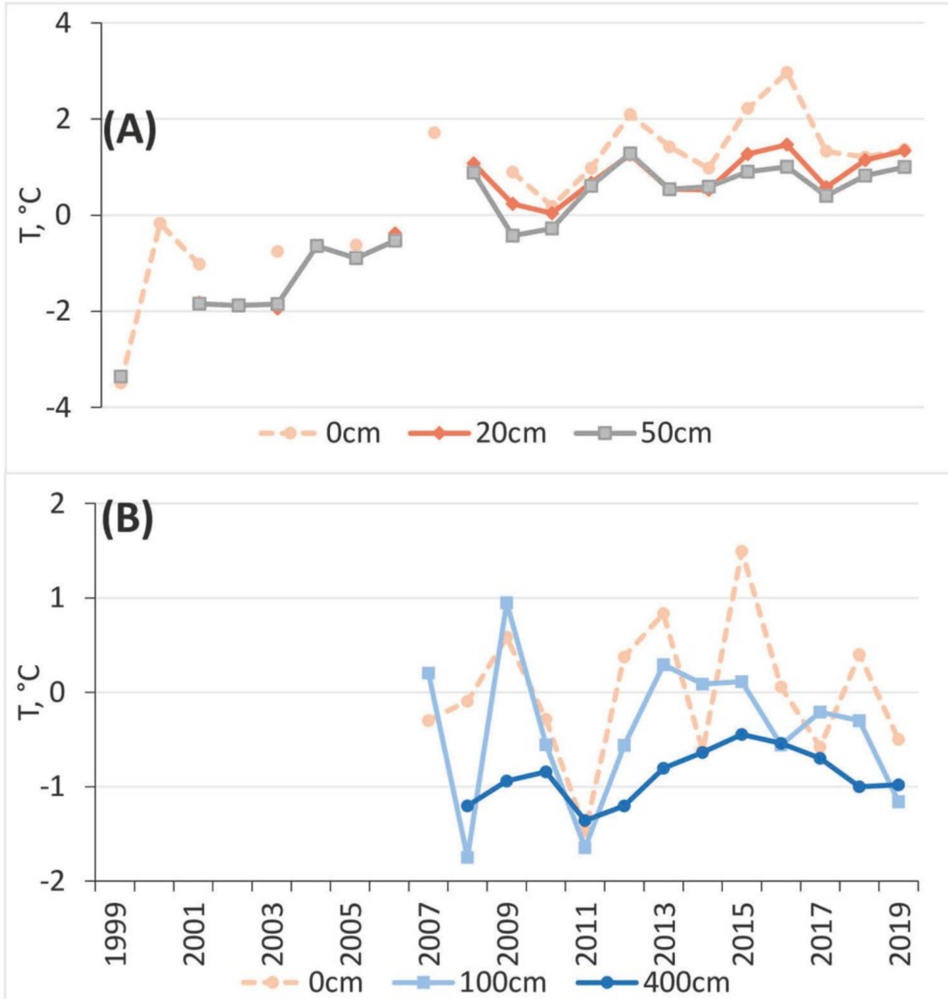

Figure 4. Dynamics of ground temperatures at Ayach-Yakha R2 (A) and Bolvansky R24 (B) CALM sites.

Organic layer thickness and height of the shrubs were measured at each site near each grid node once for the period observations. Soil profiles were classified according to the World Reference Base (WRB) soil classification system (IUSS, 2014). Additional auxiliary measurements were conducted at several sites according to the methodology described below. Volumetric water content in the upper soil layer was annually measured at individual grid nodes with a portable Delta-T SM 150 probe at R2 and R23 sites. At the R24 and R24a sites, gravimetric water content was determined by drying the soil samples, obtained in the proximity of grid nodes, in a gravity convection oven (Golden Software, 2002/2005). Snow depth was probed annually at the end of March with a graduated steel rod at the R2 site only. Ground temperatures within the active layer and of the upper permafrost were measured by Hobo U-12 data loggers programed at three-hour intervals at R2 and R24 sites. Within the active layer, the vertical array sensors were installed from the ground surface to the permafrost table with 20–25 cm intervals. In permafrost, the sensors were installed at depths of 1, 3, 5, and 10 m in accordance with the Global Terrestrial Network for Permafrost (GTN-P) protocol [Biskaborn et al., 2015].

To provide a regional spatial–temporal assessment of climatic characteristics the mean annual air temperature, thawing index (Degree Months of Thawing), and freezing index (Degree Months of Freezing) were calculated using monthly air temperature data from 25 regional meteorological stations and over the last 35 years. The atmospheric observations (e.g. daily air temperatures and daily precipitation) from Vorkuta (for R2 and R23 sites) and Naryan-Mar (for R24 and R24a sites) weather stations were used to assess relations between climate and the observed changes in the active-layer thickness. Daily air temperature data were used to calculate Degrees Days of Thawing (DDT) and Freezing Degree Days (FDD) used to analyze relations between climatic forcing and changes in the active-layer thickness.

Results

A spatial analysis of climate data from the metrological stations within the region indicates significant climatic warming throughout the Russian European North between the 1960–1990 and 2000–2015 periods (Figure 2). The isolines of the period-average Mean Annual Air Temperature (MAAT) shifted 100–200 km from SW to NE (Figure 2A). Similarly, the isolines of the Thaw Index (TI) shifted latitudinally 100–150 km to the north, while Freezing Index (FI) isolines moved up to 200 km in the north-east directions (Figure 2B, C).

Data from the meteorological stations located in close proximity to the CALM sites (Vorkuta and Naryan-Mar) presented in Figure 3 show that the Mean Annual Air temperature (MAAT) has been increasing over the 50-year period of record. The positive averaged trend of about 0.05 °C /year over the 1960–2019 period is characteristic of both locations ($p < 0.01$) (Figure 3). According to Naryan-Mar weather station data, mean annual precipitation increased over the past 40 years ($p < 0.01$) (Figure 3). During the period of active layer measurements, the linear regression coefficient (r) of MAAT was even higher: 0.31 and 0.45 respectively. The data from the Ayach-Yakha (R2) site also indicate a weak increasing trend in snow depth ($p < 0.01$) (Figure 5B).

The changes in climatic parameters (e.g. increase in MAAT, TI, FI, annual precipitation) promoted permafrost thaw manifested by the increases in Mean Annual Ground Temperature (MAGT) and the Active-Layer Thickness. Ground temperature observations conducted at the CALM sites indicate that during the 2010–2019 period, MAGTs at depths of 0–1 m at all the sites became mostly positive (Figure 4). Usually, the negative mean annual ground temperature is a characteristic of the permafrost-affected soils while positive ground temperatures occur in seasonally-frozen soils (Kudryavtsev, Poltev, & Romanovsky, 1981; Burn, 2004). Observations provided in Figure 4 indicate that over the last two decades, there was a significant increase in soil temperature at the CALM sites in the Russian European North (Kaverin et al., 2014; Malkova, 2010; Mazhitova, 2008). The trend of soil temperature increase is notable at the R2 site ($r = 0.6–0.7$; $p < 0.01$, at 0.5 m depth), and is less pronounced at the R24 site ($r = 0.2$; $p < 0.01$, at 4 m depth). The soil temperature regime has become much warmer and is approaching characteristic of seasonally frozen (non-permafrost) sub-arctic soils.

Average annual active-layer thickness as observed at these four CALM sites in the Russian European North and annual Degree Days of Thawing values from near-by meteorological stations are presented in Figure 5. Figure 6 shows the site-specific spatial distribution of the active-layer thickness values as observed in 2019 and the spatial

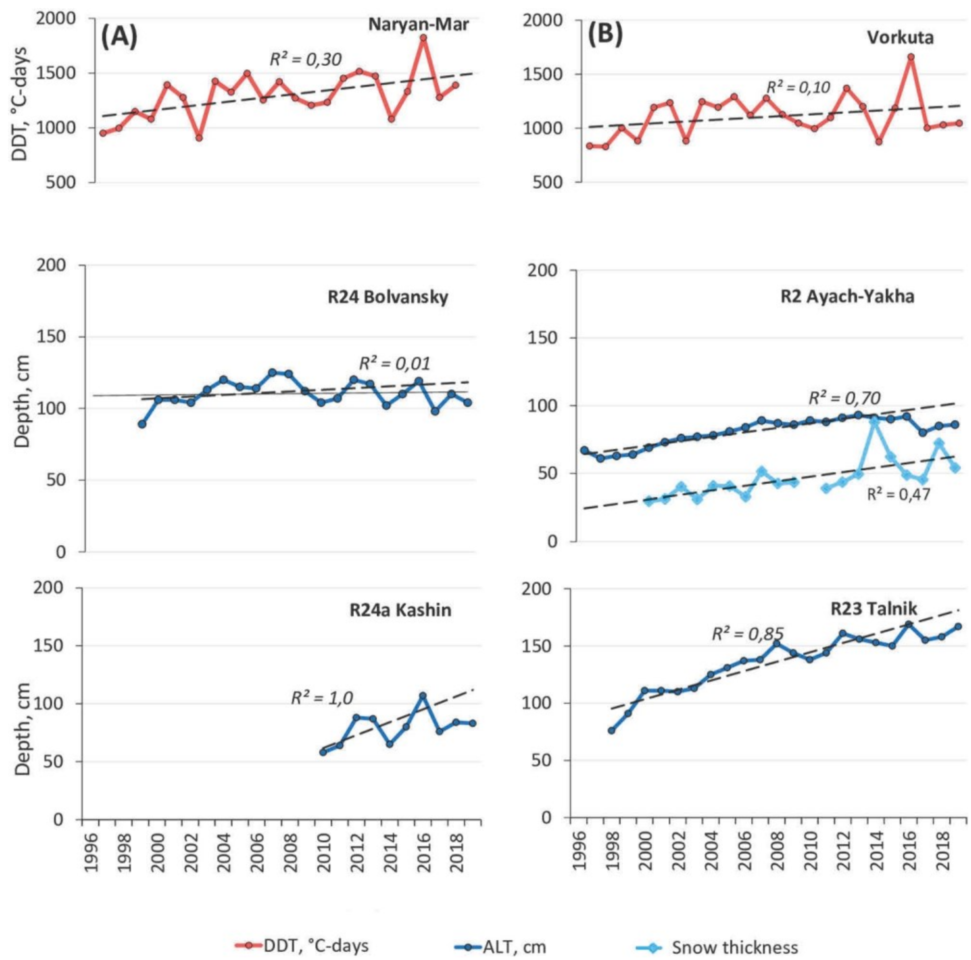

Figure 5. Dynamics of Degree Days Thaw (DDT), active layer thickness (ALT) and snow depth at CALM sites in the western (A) and (B) eastern part of the region.

distribution of active-layer change rates over the observational period. At the Bolvansky site (R24), average ALT over the 1999–2019 period increased from 89 to 104 cm at an overall rate of 0.7 cm/year ($p < 0.01$) (Figure 6A, B). The most significant ALT increase was observed at grid nodes in the southeastern part of the site (a slope of the lake depression) (Figure 6B). MAGT at depth of 0–4 m generally increased by 0.2–1.0ºC, with a small positive trend (0.01–0.03ºC/year) (Figure 4).

At the Kashin Island (R23a) site, averaged ALT increased by nearly a factor of two, from 58 cm in 2010–83 cm in 2019, contributing to a very high rate of active-layer thickening of 2.5 cm/year ($p < 0.01$) (Figure 6C, D). The largest increase of ALT was observed in the upland part of the site. The minimum thaw depth (40–50 cm) was observed in the poorly drained parts of the site, where the peat layer is 0.20–0.25 m thick, while the largest ALT values (100–110 cm) were observed in drained areas with shallow (about 5 cm) peat layers.

At the Ayach-Yakha (R2) site, the average ALT increased from 67 to 86 cm during the 1996–2019 period. The site-averaged rate of active-layer increase over the 1999–2019

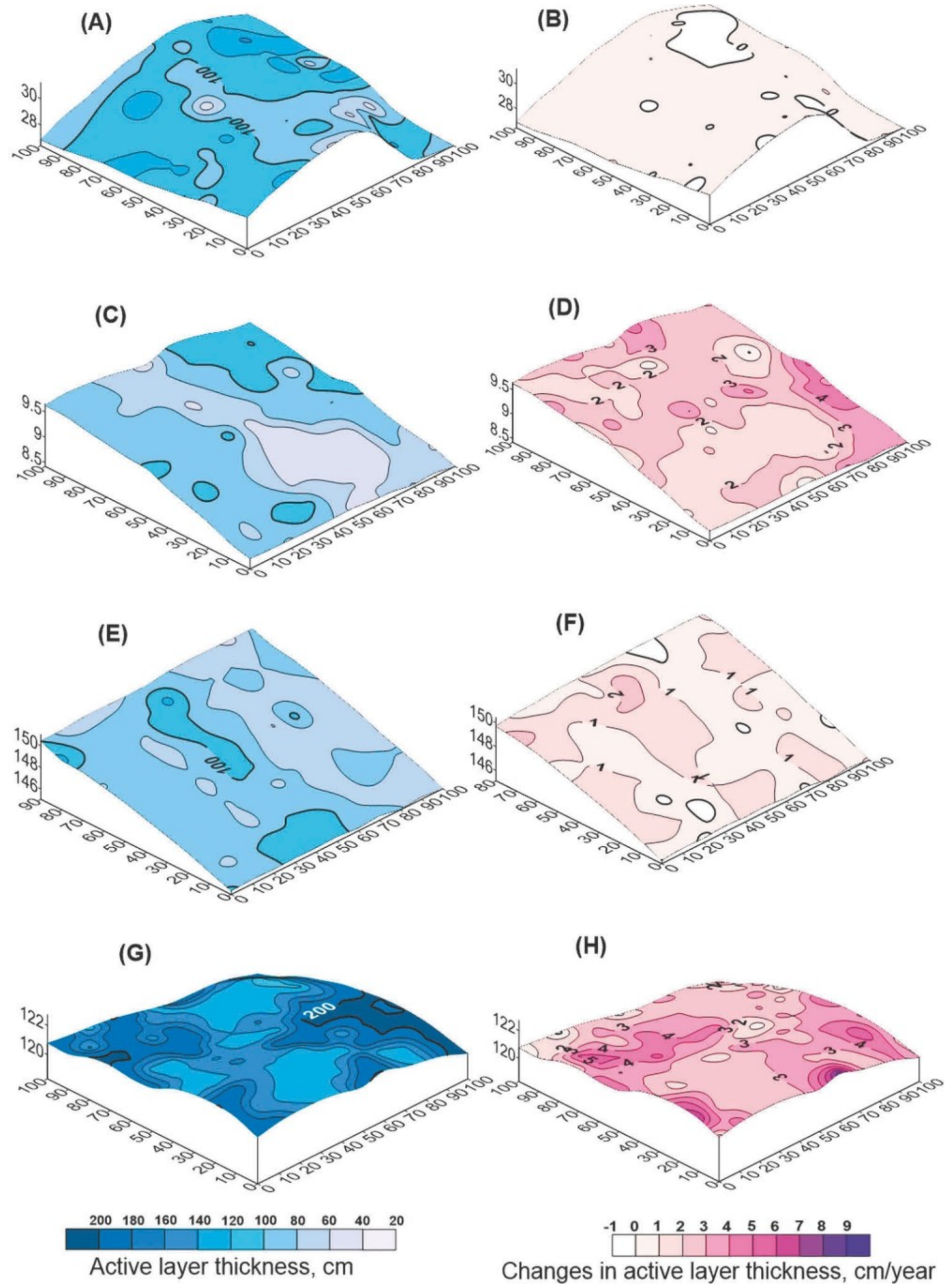

Figure 6. Active layer thickness (ALT) at Bolvansky R24 site in 2019, cm (A); Changes in ALT at Bolvansky R24 site, 1999–2019, cm/year (B); ALT at Kashin Island R24a site in 2019, cm (C); Change in ALT at Kashin Island R24a site, 2010–2019, cm/year (D); ALT at Ayach-Yakha R2 site in 2019, cm, (E); Change in ALT at Ayach-Yakha R2 site, 1996–2019, cm/year (F); ALT at Talnik R23 site in 2019, cm (G); Change in ALT at Talnik R23 site, 1998–2019, cm/year (H). All the scales are shown in meters. Vertical scale shows meters above sea level.

period was 0.8 cm/year ($p < 0.01$). The most pronounced thickening of the active layer was observed in the upland part of the site and along the hollow crossing the grid downslope (Figure 6E, F).

At the Talnik (R23) site, averaged ALT increased steadily, from 76 cm in 1998–167 cm in 2019. During the 1998–2008 period, ALT doubled, from 76 to 152 cm (Figure 5). The site-averaged trend over the study period was 4 cm/year ($p < 0.01$) (Figure 6 G, H). The most intensive ALT increase was observed in the lower (southern) part of the site.

Discussion

From 1996 until 2007, the active-layer thickness at all sites was increasing almost steadily. During that period, permafrost thaw can be attributed primarily to the increase in air temperature. From 2008 to 2019, changes in site-averaged ALT values varied between sites. While site R23 has experienced a continued thickening of the active layer, the ALT trends at other sites weakened (Figure 5). Both winter and summer temperatures over the 2008–2019 period were generally warmer in comparison to the 1995–2007 period. Nevertheless, since 2008, the increase of air temperature has slowed down which can explain the relative stabilization of ALT over recent years.

The largest ALT increase was observed at R23 and R24a sites (Figure 5). Pronounced positive ALT trends at these locations could be the result of present-day talik formation provoking intensive permafrost thaw. Earlier regional studies (e.g. Oberman & Shesler, 2009) indicate that intensive talik formation is accompanied by permafrost degradation throughout the Russian European North. As a result, the soil thermal regime has changed drastically from being perennially frozen to freezing seasonally.

Statistical analysis of correlations between site-specific climatic parameters and ALT are presented in Table 1. For the observation period, the highest correlation coefficients were between ALT and Freezing Degree Days (FDD), as well as MAAT at the R23 and R24a sites. These sites have been experiencing the most intensive permafrost thaw (Table 1). In a previous study (Mazhitova & Kaverin, 2007), a statistically significant correlation (r = 0.6) was found between ALT and DDT values for 1999–2006 at the R2 site. During the

Table 1. Correlation between ALT and climatic factors (Vorkuta and Naryan-Mar meteorological stations): correlation coefficient (upper value); –;– significance level (middle value), – t-value (lower value).

Site, climatic factor	MAAT	DDT	FDD	MAP	Snow depth
Vorkuta					
ALT, R-2	0.593	0.492	0.561	0.457	0.580*
	0.005	0.023	0.008	0.043	0.015*
	45	−26	30	−22	13
ALT, R-23	0.727	0.318	0.766	0.174	0.539*
	0.001	0.198	0.000	0.490	0.031*
	27	−26	28	−20	25
Naryan-Mar					
ALT, R-24	0.537	0.508	0.506	−0.068	0.501
	0.022	0.037	0.046	0.803	0.116
	62	−28	21	−26	9
ALT, R-24a	0.831	0.574	0.742	0.281	–
	0.020	0.178	0.056	0.647	–
	17	−20	–	−24	–

*data from R2 site. The fields were: MAAT = Mean Annual Air Temperature; DDT = Degrees Days of Thawing; FDD = Freezing Degree Days; MAP = Mean Annual Precipitation; ALT = Active Layer Thickness.

last decade (2008–2019), it appears ALT dynamics have been more affected by the winter air temperature regime. Still, relatively high ALT-DDT correlation coefficients were observed for the sites located in the northern part of the Pechora Lowland (Bolvansky R-24, Kashin Island R-24a). Variability and change in annual snow cover (Figure 5) also seem to contribute to the interannual dynamics of the active-layer thickness (Table 1). The smallest correlation coefficients are found between the ALT and mean annual precipitation.

A gradual increase in MAGT strongly affects ALT. At the R2 and R24 sites, the bottom of the active layer remained unfrozen during the warmest winters of the last decade. The occurrence of such events triggers further permafrost thaw and talik formation, and these phenomena persisted through subsequent colder years [Malkova et al., 2016].

The Ayach-Yakha R2 site, despite consistently positive MAGT, reacts to climate warming rather slowly. This confirms earlier results, which were based on a much shorter observational record from R2 site (Mazhitova et al., 2004). The small rate of ALT increase at the R2 site can be attributed to the high ground ice content in the transient layer, which is considered to act as a natural buffer protecting permafrost from rapid thaw due to latent heat effects (Shur et al., 2005). All other sites have higher interannual ALT fluctuations and react to climatic changes much more rapidly (Figure 5).

Spatial variability in the active-layer thickness at Russian European CALM sites is controlled primarily by organic layer thickness (Mazhitova, 2008; Mazhitova et al., 2004; Mazhitova & Kaverin, 2007). Compared to Cryosols with peat horizons less than 10 cm thick, Histic Cryosols (peat horizons 10–30 cm thick) found in the region usually have colder ground thermal regimes and shallower annual thaw propagation. Statistical analysis

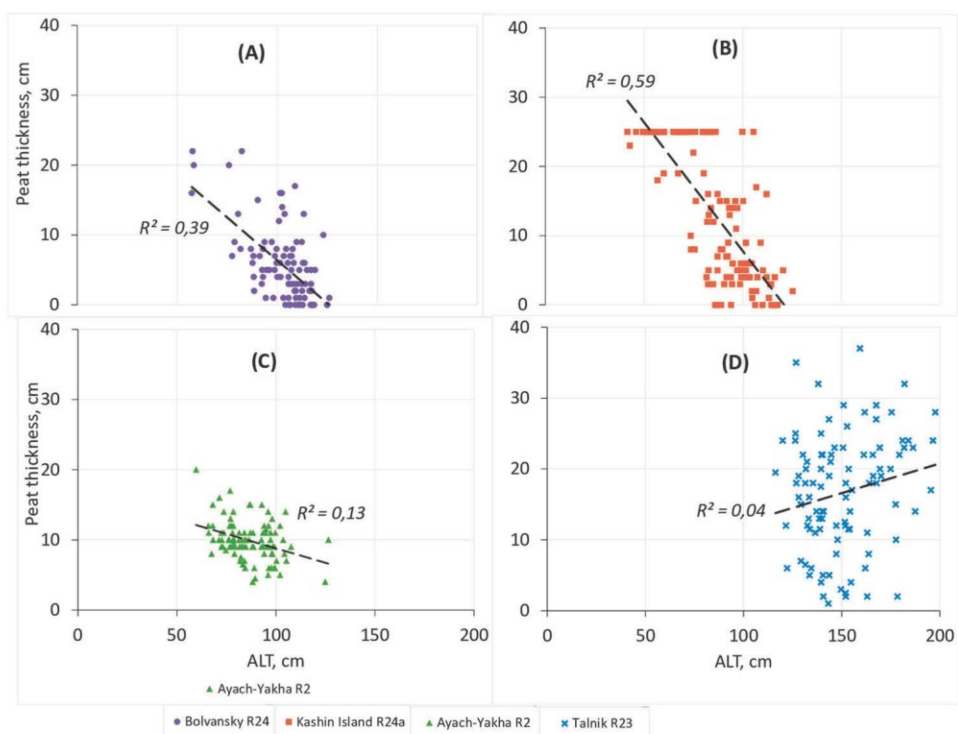

Figure 7. Relation between active layer thickness in 2016 and peat thickness in European CALM sites: Bolvansky R24 (A); Kashin Island R24a (B); Ayach-Yakha R2 (C); Talnik R23 (D).

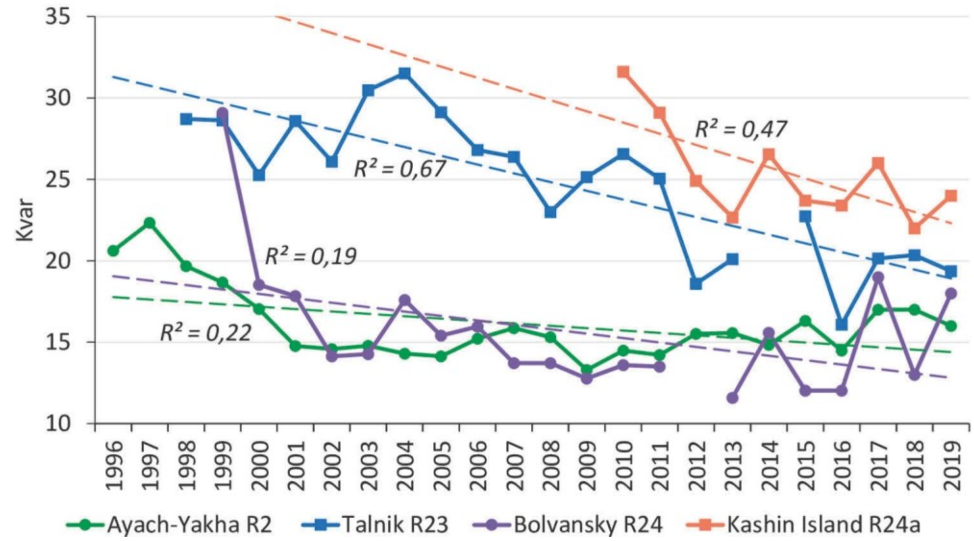

Figure 8. Coefficients of variation of site-averaged active layer thickness in European CALM sites.

revealed that thicker peat layers reduce ALT. However, the overall insulating of peat varies between sites (Figure 7). Peat appears to have the greatest influence on ALT on the R23a site, which has a thicker and more spatially differentiated peat horizon. No correlation is apparent at Talnik, which can be explained by the relatively thin peat layer there.

Analysis of site-averaged ALT coefficients of variation, calculated for each year, reveals differences in spatial ALT heterogeneity between all sites. The R2 and R24 sites have similar, relatively small long-term averaged coefficients of variation (16 ± 5%) in comparison to those estimated for the R23 and R24a sites (25 ± 7%) characterized by more pronounced observed thaw (Figure 8). Higher coefficients of variation at R23 and R24a sites can be explained by the presence of stable closed talik zones. Over the observation period, all sites have experienced a gradual decrease in the coefficient of variation, and this appears to be associated with a general lowering of the permafrost table. Such dynamics may be explained by the reduction in the influence of surface factors, such as an organic layer, snow, and vegetation, which accompanies the deepening of the permafrost table.

Conclusions

Over the past two decades, active layer thickness (ALT) has increased at all Russian European CALM sites. Site-averaged ALT showed strong positive trends, varying from 0.3 to 3.0 cm per year. Permafrost thaw was caused primarily by an increase in both summer and winter air temperatures and snow depth. Consequently, there was a rise in active layer temperatures, which became mostly positive during the last decade signifying a transition from perennially to seasonally frozen ground. The largest ALT increase was observed at sites characterized by greater spatial variability in ALT associated with talik formation. The spatial variability of ALT at sites examined is mostly controlled by organic layer thickness. However, the long-term deepening of the permafrost table has resulted in a gradual decrease in spatial heterogeneity of ALT, indicating a decrease in the overall influence of landscape factors (surface peat horizon and vegetation) on the permafrost thaw.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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