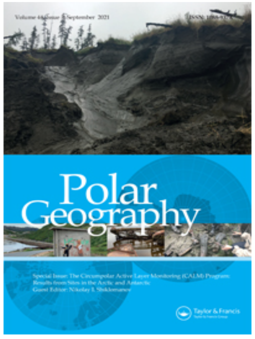

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Two decades of active layer thickness monitoring in northeastern Asia

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ABSTRACT

This study summarizes seasonal thawing data collected in different permafrost regions of northeast Asia over the 1995–2018 period. Empirical observations were undertaken under the Circumpolar Active Layer Monitoring (CALM) program at a range of sites across the permafrost landscapes of the Yana-Indigirka and Kolyma lowlands and the Chukotka Peninsula, and supplemented with 10 years of observations from volcanic mountainous areas of the Kamchatka Peninsula. Thaw depth observations, taken using mechanical probing at the end of the thawing season, and ground temperature measurements, were analyzed with respect to air temperatures trends. The data from 24 sites (16 in the Indigirka-Kolyma region, 5 in Chukotka and 3 in Kamchatka) reveal different reactions of the active layer thickness (ALT) to recent changes in atmospheric climate. In general, there is a positive relation between ALT and summer air temperatures. Since the early 2000s positive ALT anomalies (compared with mean data from all sites) prevail in the Kolyma and Chukotka area, with only one alas site showing a negative ALT trend. The only active site in the Kamchatka Mountains shows no significant thaw depth changes over the period of observation. Two other Kamchatka sites were affected during a volcanic eruption in 2012.

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Introduction

The active layer is the uppermost layer of ground in permafrost terrain. It thaws in summer and refreezes during the cold season (Muller, 1947). The active layer thickness (ALT) is an important integrated parameter that can reflect the impact of climate changes in permafrost regions (Brown, Hinkel, & Nelson, 2000). The thickness of the active layer can be inferred from the thaw depth observations collected at the end of the warm (thawing) season. Since the beginning of the 1990s, the international Circumpolar Active-Layer Monitoring (CALM) program has been collecting annual end-of season thaw depth data from more

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than 200 sites around the world (see details in Brown et al., 2000). In the vast area of northeast Asia underlain by permafrost, CALM sites are located in three geographically distinct areas: the Yana-Indigirka and Kolyma lowlands, Chukotka, and the Kamchatka peninsula (Figure 1). It should be noted that Kamchatka differs greatly from the other permafrost regions, as the mountain permafrost there is affected locally by volcanic activity (Abramov, Gruber, & Gilichinsky, 2008). This report presents the results of 23 years of ALT monitoring in the Yana-Indigirka and Kolyma lowlands and Chukotka, and more than 10 years for Kamchatka. Although significant efforts were placed on adhering to standardized observational methodology for active layer thickness according to the CALM protocol (discussed below), the large size of the regions discussed in this report, local landscape variability, and logistical difficulties have led to significant constraints on data analysis. As a result, the spatial sampling strategy and availability of climate, ground temperature, and other auxiliary data vary between regions and individual sites.

Study areas

Yana-Indigirka and Kolyma lowlands (Northern Yakutia)

The Yana-Indigirka-Kolyma region is located in the Arctic coastal lowlands of northeastern Yakutia, bordered by the Indigirka and Kolyma rivers (68°–72°N, 147°–162°E, Figure 1(a)). The region encompasses a transitional zone between boreal forest (northern taiga) ecosystem in the south and tundra ecosystems in the north. It is located on the vast accumulative plains formed mostly by the Late Pleistocene loess-like Yedoma Ice Complex, characterized by high ice and organic matter content (Murton et al., 2015; Sher et al., 1979; Schirrmeister, Froese, Tumskoy, Grosse, & Wetterich, 2013). Thawing of Yedoma deposits during the Holocene resulted in numerous thermokarst lake basins (or alases) and vast marine transgression (Gavrilov, Romanovsky, & Hubberten, 2006; Kaplina, 2009; Veremeeva & Glushkova, 2016). The region is underlain by permafrost almost continuously, with thickness of up to 500–600 m and mean annual ground temperatures (MAGT) of −8 to −11°C within the tundra and −7°C to −8°C in the taiga (Yershov, Kondratyeva, Loginov, & Sychev, 1991). In the Akhmelo Lake area (sites R17, 19, 21), located in the forest-tundra, MAGT is higher (−3 to −4°C), which is probably attributable to the high geothermal flux associated with the fault zone depicted on a geological map of the area (Harrison et al., 2008). The very high ice content (up to 90%) of Yedoma deposits in the Yana-Indigirka and Kolyma lowlands (Shmelev et al., 2017; Trush & Kondratyeva, 1975) makes them extremely vulnerable to climate warming. Recent climate-induced increases in thaw propagation have triggered changes in local relief in Yedoma uplands, including soil subsidence (Günther et al., 2015), activation of thermokarst and thermoerosion processes, and expansion of pond and thermokarst lake areas (Grigoriev, Kunitsky, Chzhan, & Shepelev, 2009; Nitze et al., 2017).

There are 16 active CALM sites in the Yana-Indigirka and Kolyma lowlands region, representing subzones of typical tundra, southern tundra, and northern taiga (Table 1, subzones classification according to Matveyeva, 1998). Sites are located at elevations ranging from 10 to 15 m a.s.l. for alases to 20–40 m a.s.l. for Yedoma uplands. One Yedoma site (R18) with northern taiga vegetation is located at 150 m a.s.l. at the footslope of Mount Rodinka. Most of the sites are dominated by Turbic Cryosols Loamic soils. Only three sites (R16, R19 and R21) contain Turbic Cryosols Arenic soils (WRB, 2015), representing late Holocene limnic-palustrine deposits of Khalerchinskaya Tundra (Ivanenko, 1998). The sites were selected to represent the main

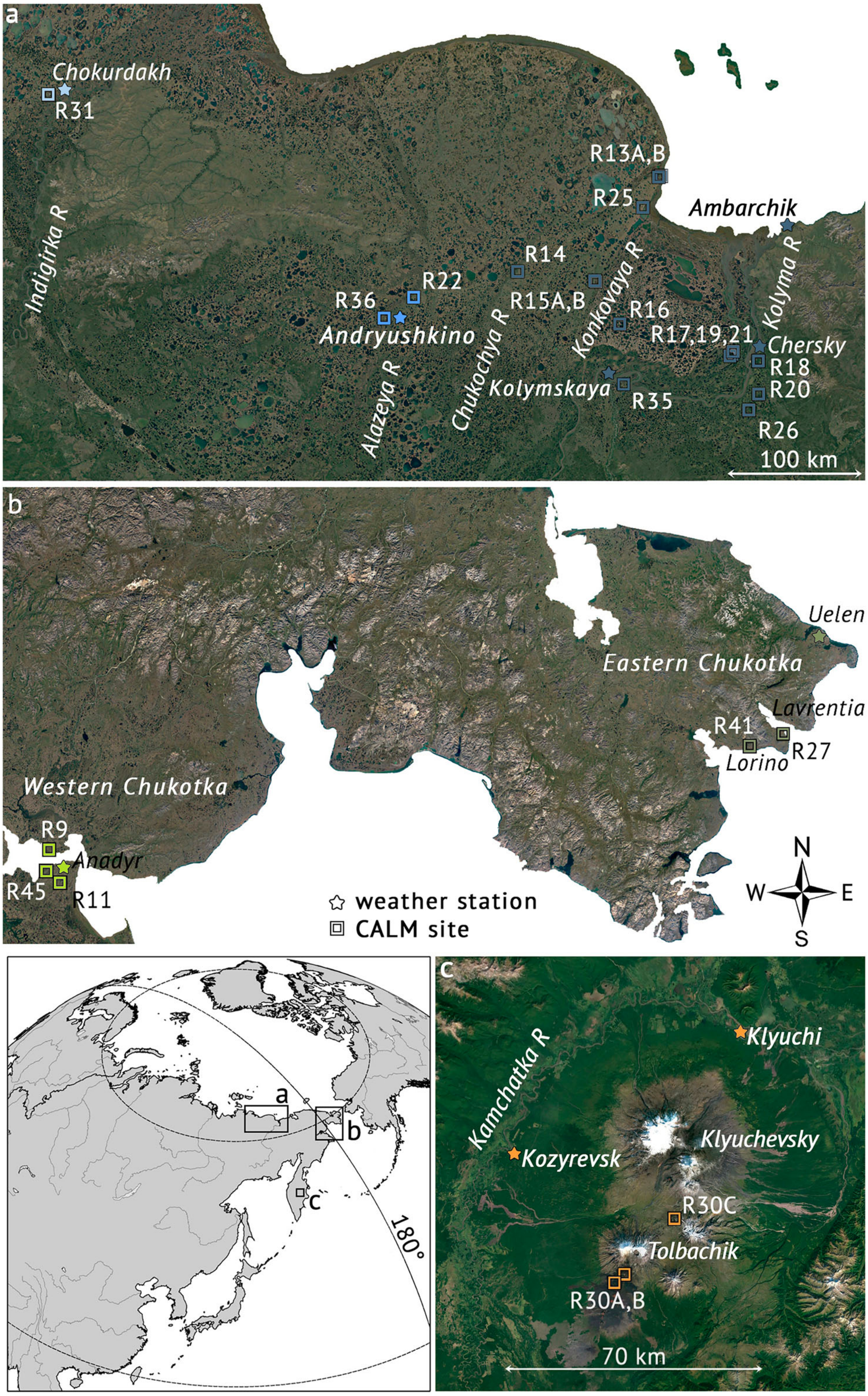

Figure 1. Study area. Indexes correspond to Circumpolar Active Layer Monitoring (CALM) site designations. A Landsat 8 image is used for background. Further information about sites is available at https://www2.gwu.edu/~calm/data/north.html.

Table 1. Parameters of the sites (refer to Figure 1 for locations). Mean ALT numbers calculated for the whole period of measurements. The ALT extremes for each region are marked in bold (the lowest, maximal mean and deepest for all period of observations).

#	Code	Name	Vegetation	Mesorelief	Soil	ALT, cm Min/Med/Max
Indigirka-Alazeya region						
1	R22	Alazeya River	southern tundra	yedoma upland	loamy	45/**52**/**57**
2	R31	Allaiha River	southern tundra	yedoma upland	loamy	39/46/52
3	R36	Andryushkino Village	northern taiga	river floodplain, bog forest	loamy	**31**/39/44
Kolyma region						
4	R13A	Maliy Chukochiy Cape	typical tundra	yedoma upland	loamy	33/43/55
5	R13B	Maliy Chukochiy Cape	typical tundra	alas	loamy	25/40/56
6	R14	Bolshaya Chukochya River	southern tundra	yedoma upland	loamy	38/44/49
7	R15 A	Malaya Konkovaya River	southern tundra	alas	loamy	25/35/60
8	R15 B	Malaya Konkovaya River	southern tundra	yedoma upland	loamy	32/43/54
9	R16	Segodnya Pingo	southern tundra	polygonal bog	sandy	30/53/75
10	R17	Akhmelo River	southern tundra	river floodplain	loamy	43/54/64
11	R18	Mt. Rodinka	northern taiga	yedoma upland	loamy	72/80/87
12	R19	Glukhoe Lake	northern taiga	watershed	sandy	56/86/112
13	R20	Malchikovskaya Channel	northern taiga	river floodplain	loamy	46/55/65
14	R21	Akhmelo Lake	southern tundra	flat watershed	sandy	70/**97**/**117**
15	R25	Yakutskoe Lake	southern tundra	yedoma steep slope	loamy	**23**/46/65
16	R35	Omolon River	southern tundra	yedoma, bog forest	loamy	32/41/52
Western Chukotka region						
17	R9	Cape Rogozhny	typical tundra	hilly plain	loamy	**38**/51/60
18	R11	Mt. Dionisy	typical tundra	slope	loamy	45/**56**/**67**
21	R45	Mt. Kruglaya, Anadyr Village	typical tundra	lake-marsh basin	peaty	42/46/49
Eastern Chukotka region						
19	R27	Lavrentia Village	typical tundra	slope	loamy	59/**66**/**78**
20	R41	Lorino Village	typical tundra	coastal plain	sandy	**47**/52/56
Kamchatka region						
22	R30A	Mt. Tolbachik (south slope)	no	plain, 1330 m a.s.l.	scoria	67/**73**/**80**
23	R30B	Mt. Tolbachik (south slope)	no	plain, 1600 m a.s.l.	scoria	49/55/63
24	R30C	Mt. Tolbachik (north slope)	no	plain, 1630 m a.s.l.	scoria	**44**/49/53

landscape categories (Yedoma uplands, alases, watersheds and floodplains) of the three broad vegetation zones (northern taiga, southern tundra, typical tundra). Sites located in the northern taiga zone of the Kolyma Lowland are covered by larch forest with willow, birch shrubs, and a ground cover rich in mosses and lichens. The typical zonal tundra vegetation of the Yedoma uplands includes dwarf willows and shrubs with graminoids, carex, and cotton grass over various species of lichens and mosses. Alas landscapes are characterized by polygonal complexes, developed in the thermokarst lake basins on poorly drained flat surfaces of degrading Yedoma and covered by tundra vegetation, including carex and sphagnum mosses. Watersheds on sandy deposits of Khalerchinskaya Tundra are ice-poor and better drained. Floodplain vegetation is represented by numerous species of willow meadows along stream channels and lake terraces, as well as cotton grass marshes. A detailed description of regional features was provided in Fyodorov-Davydov et al. (2004).

Chukotka

Four CALM observational sites in Chukotka are located on the coastal plain of the Bering Sea, in the vicinity of the Anadyr, Lorino, and Lavrentiya settlements (Figure 1(b)). The sites with long series of observations (R9, 11, 27) are described in detail by Zamolodchikov, Kotov, Karelin, and Razzhivin (2004). Observations near Anadyr were initiated in 1994 in the typical tundra zone at three monitoring sites representing characteristic zonal landscapes of the Anadyr area. Site R9 represents gently sloping plains composed of peaty sandy loam and covered with hummocky moss-sedge tundra. Site R11 is located in a foothills landscape at 140–145 m a.s.l. elevation. It is characterized by loam deposits with gravel inclusions and covered with moss and shrub tundra. Wet polygonal lowlands (10–20 m a.s.l.) developed in drained lake basins with peaty and loamy deposits and hummocky shrub-moss-sedge tundra are represented by Site R45.

Observations in eastern Chukotka near the Lavrentiya settlement were initiated in 2000 at 50–70 m a.s.l. elevation. The monitoring sites represent two landscapes of Eastern Chukotka: (1) marine-glacial plains with sedge and moss tundra vegetation developed on peaty loam deposits with Histic Cryosols Loamic soils (WRB, 2015) (site R27); and (2) peatlands covered with rich lichen and shrub vegetation (site R41).

All Chukotka sites are located within the continuous permafrost zone. Near Anadyr, taliks are found only beneath Onemen Bay and large lakes. Permafrost thickness ranges from 100 to 300 m, with MAGT of −3 to −5°C. In eastern Chukotka continuous permafrost has 200–400 m thickness, and the MAGT of −5 to −7°C. Ice wedges and massive ice bodies are widespread in the area.

Kamchatka

The Klyuchevskaya Volcano group is situated in the Central Kamchatka Depression (55–56° N, 160–161°E, Figure 1(c)), and consists of the active volcanoes Klyuchevsky, Bezymianny, Ushkovsky, and Tolbachik. Numerous volcanogenic landforms, such as cinder cones or extrusive domes with lava plateaus and plains, are common in the region. The closest weather stations are situated in the Kozyrevsk and Klyuchi villages at the valley bottom level at 30 m a.s.l., 30–50 km from the summits, which range from 3000 to 4800 m a.s.l. in elevation.

Volcanic footslopes are forested, with vegetation zones largely controlled by elevation. Deciduous forests are common below 200 m a.s.l., coniferous forest below 400 m a.s.l., stone birch forest below 900 m a.s.l., shrubs and dwarf trees up to 1200 m a.s.l., mountain tundra up to 2000m a.s.l., and isolated patches of grass and lichen at elevations of up to 2500 m a.s.l. Soils here are mainly Turbic Cryosols Andic Tephric (WRB, 2015).

Permafrost in Kamchatka is present primarily at high mountainous elevations. Generally, permafrost is continuous above 900–1000 m a.s.l. At elevations of 1300–1600 m a.s.l. it has thickness up to 100–150 m, and MAGT about −2.5°C to −3.5°C (Abramov et al., 2008). Surface deposits consist of volcanic scoria. The vegetation cover within the sites consists of very sparse patches of graminoids, moss, and lichens, often arranged in narrow strips along the borders of polygonal features (Figure 2).

Three sites were originally established in Kamchatka to cover a range of elevations and exposure settings: two (R30A and R30B) on the southern slope of Tolbachik volcano at 1300 and 1600 m a.s.l. and one (R30C) at the northern slope at 1600 m a.s.l. (Figure 2). Both southern slope sites were dramatically affected by a large fissure eruption in 2012, making thaw depth observations impossible.

Methodology

Following the CALM protocol (Fagan & Nelson, 2017; Nelson & Hinkel, 2003; Nelson, Shiklomanov, & Mueller, 1999), a 1.5–2 m long steel probe was used to mechanically measure the end-of season thaw depth. The Indigirka-Kolyma and Chukotka

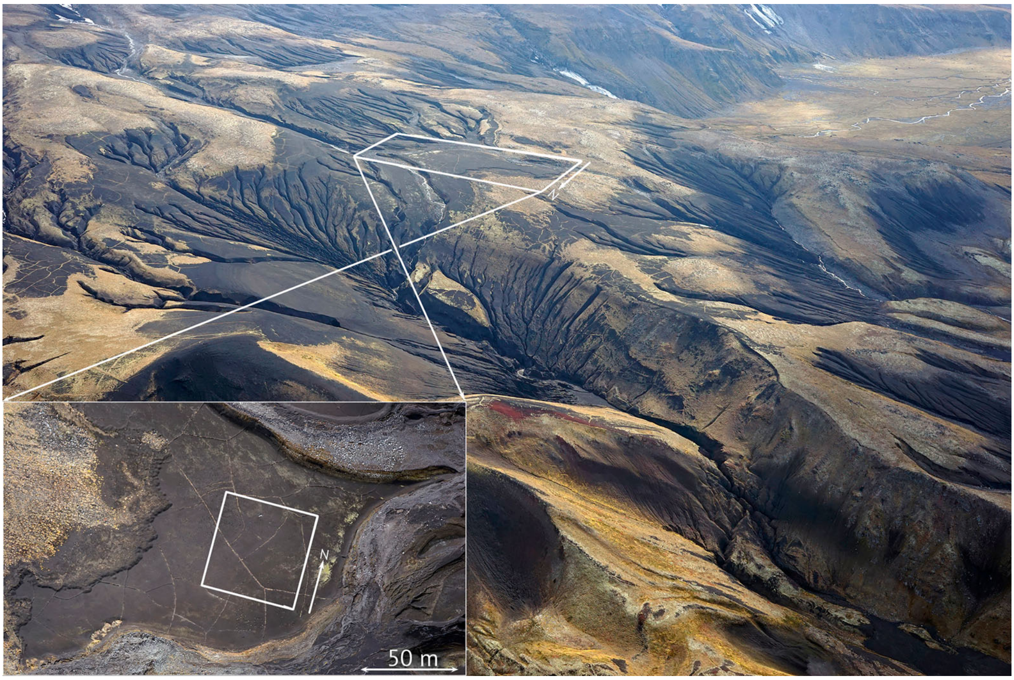

Figure 2. Aerial view of R30C grid (outlined in white box). The polygonal frost cracking features and the results of thermo erosion are clearly visible. Photo: Andrey Abramov.

sites consist of a 1 ha lattice of observation points spaced at regular 10 m intervals and arranged in rows aligned with the cardinal directions.

As a result, each site consists of 121 observational points. Owing to the limited extent of surfaces where mechanical thaw depth probing is possible, the mountainous areas of Kamchatka have smaller 0.5 ha grids with 5 m spacing between points, resulting in 121 individual thaw depth samples. However, effective probing of the Kamchatka grids can be accomplished only where the thickness of volcanic scoria, sand, and ash overlying the lava deposits is greater than ALT and the presence of rock material is minimal. In areas with conditions difficult for probing, measurements made with a steel probe were verified by excavating test pits (where possible) and by ground temperature measurements from nearby boreholes (if available).

For all sites, 121 individual point observations were averaged to obtain one annual site-specific value of the end-of-season thaw depth, which provides a proxy for the annual thickness of the active layer.

Within the study area, annual thawing generally reaches its maximum depth between late August and early October, depending on year and region. Since dates when maximum annual thaw depth is reached are hard to predict in advance and owing to logistical difficulties associated with distances between sites, annual thaw depth measurements at each site/region are conducted at various times: from late August to early October for the Indigirka-Kolyma area, late August to September for Chukotka, and late September for Kamchatka. Although the dates of annual measurements vary between sites/regions, at each individual site thaw depth is measured consistently within the few-days interval of each year over the period of observations.

Consistency in the site-specific periods of annual thaw depth observations provides robustness in the analysis of long-term active-layer trends for each site/region. However, the variability in the dates of annual thaw-depth measurements between sites/regions creates some concern about the comparability of absolute active layer thickness values obtained from different sites and in different years. To address this issue, several CALM sites have thermometric boreholes, equipped with loggers for year-round surface and ground temperature monitoring, in close vicinity to the thaw depth monitoring grids. Such data help to determine the time of maximum thawing and verify the actual ALT. However, within the study area only a few sites have established long-term ground temperature monitoring system.

Previous active layer investigations conducted within the study area (e.g. Fyodorov-Davydov et al., 2004) have indicated that summer air temperatures control long-term thaw depth trends more than all other factors. Since no sites have an on-site air temperature record, the daily summer (June through August) air temperature observations from nearby weather stations were used to evaluate trends in mean summer air temperatures and cumulative degree-days of thaw (DDT) for the 1995–2018 period. Five weather stations (Chokurdakh, Andryushkino, Kolymskaya, Ambarchik and Chersky) were used for the Kolyma-Indigirka lowland region, two (Anadyr and Uelen) for the Chukotka region and two (Kozyrevsk and Klyuchi) for Kamchatka. Weather station data were obtained from publicly available Russian (meteo.ru) and U.S. (www.ncdc.noaa.gov) climate data archives. Locations of weather stations in relation to CALM sites are shown in Figure 1.

In Kamchatka, the climate data are only available for lowlands: Kozyrevsk and Klyuchi weather stations are located at 30 m a.s.l. As such, the data record does not fully represent climatic conditions at higher elevations. To address this problem, the weather station data were supplemented with the ground-surface temperature observations from the loggers installed at CALM sites in order to characterize summer air temperature conditions at the Kamchatka sites.

Results

The Degree Days of Thawing (DDT), estimated using weather station data and results from annual end-of-season thaw depth measurements at individual sites, are shown in Figure 3.

DDT trends indicate that all regions within the study area experienced a moderate increase in summer DDT over the last 20 years (Figure 3(a)). However, climatic variability was not synchronous and differs by region. For example, the maximum DDT value was observed in 2007 in the Indigirka-Kolyma region and in 2016 in the Chukotka and Kamchatka regions. Local peaks in DDT values were recorded in 2005, 2010, and 2014 for Indigirka-Kolyma; in 2004, 2007, 2010 for Chukotka, and in 2003 and 2006 for Kamchatka (Figure 3(a)).

Site-specific and regional thaw-depth trends

Because the study area extends for more than 1800 km from east to west and is characterized by a wide range of climatic and landscape conditions, the CALM observation sites were grouped according to geographic location into six sub-regions: Indigirka (site R 31) (Figure 3(b)), Alazeya (sites R22 and R 36) (Figure 3(b)), Kolyma (Figure 3(c)), Western

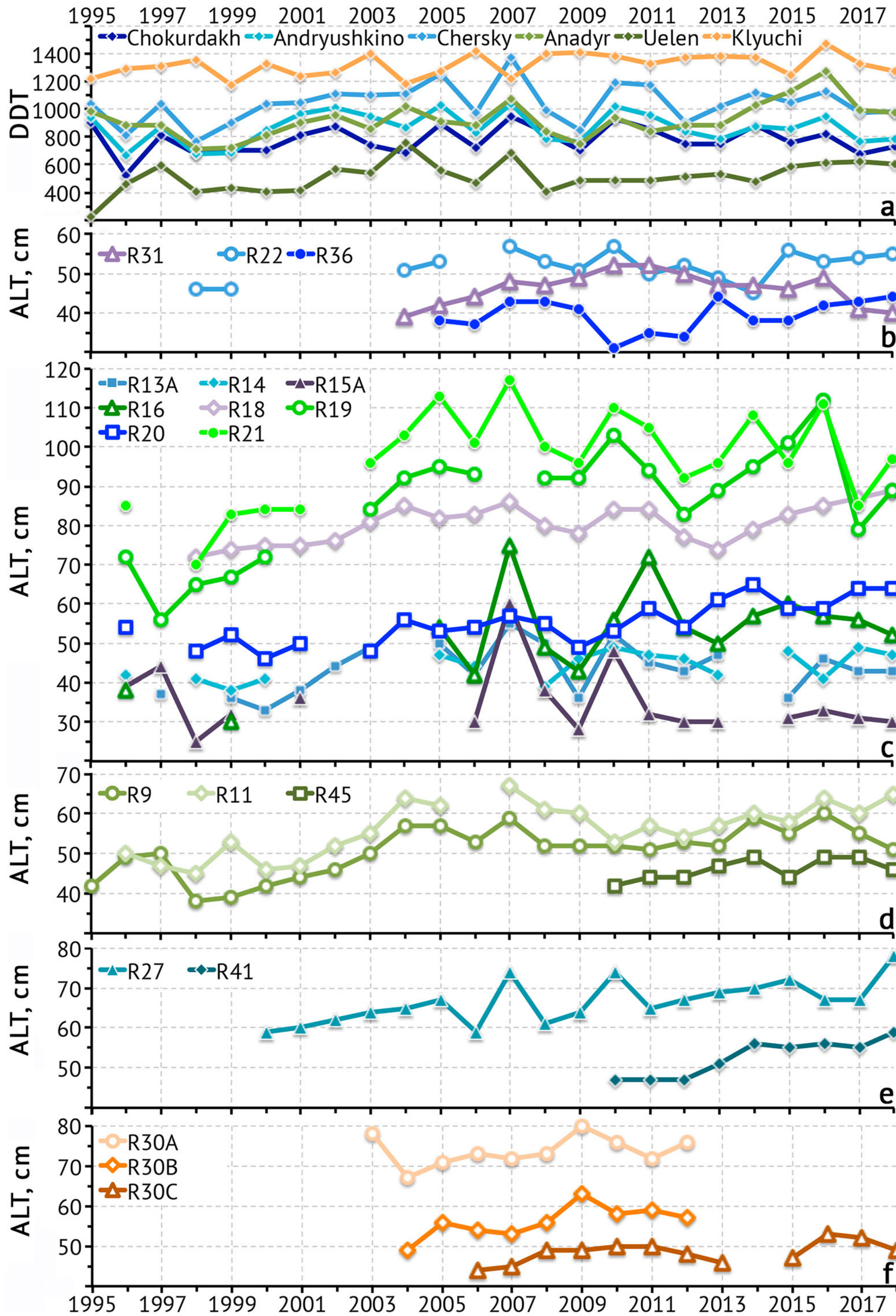

Figure 3. Variability of measured mean annual ALT compared with DDT dynamics: (a) DDT(JJA) according to weather stations (locations of weather stations are shown at Figure 1); ALT data for Indigirka (R31) – Alazeya (R36,R22) (b), Kolymka (c), Western (d) and Eastern (e) Chukotka and Kamchatka (f) sectors.

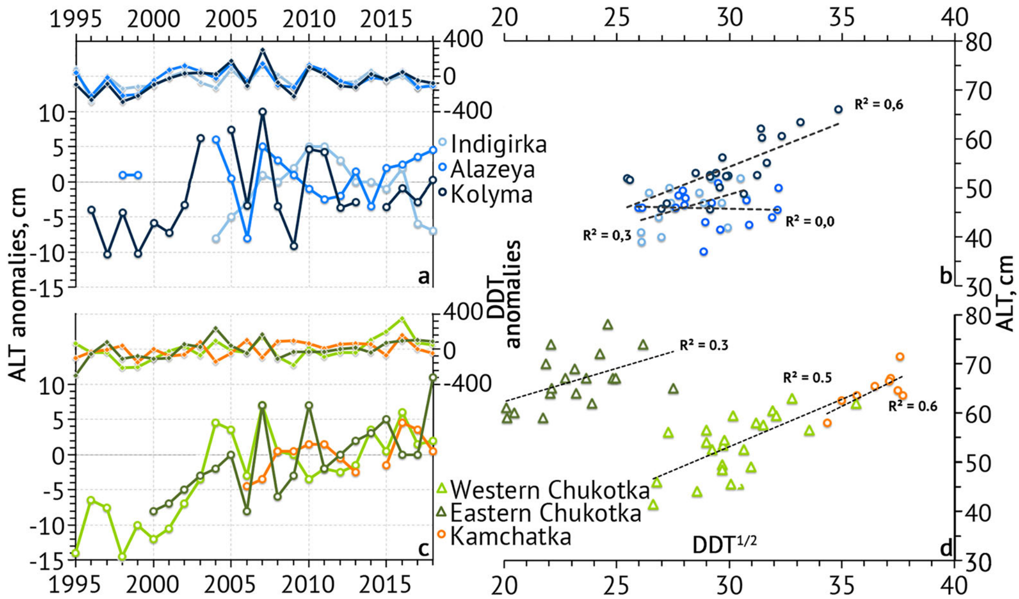

Figure 4. Long-term active-layer change in the Indigirka – Kolyma region (a). The data are presented as annual anomalies (in cm) from the mean value for the period of observation: 46 cm for Indigirka and Alazeya, 56 cm for Kolyma. Anomalies of mean DDT according to weather stations are shown for comparison; Correlation of ALT and $DDT^{1/2}$ for different parts of Indigirka – Kolyma region (b). Mean ALT values for all sites in selected area (according to Table 1) were used; Long-term active-layer change in Chukotka and Kamchatka regions (c). The data are presented as annual anomalies (in cm) from the mean value for the period of observation: 53 cm for western Chukotka (sites R9, 11), 67 cm for eastern Chukotka (site R27,) and 65 cm for the Kamchatka Peninsula (sites R30A,B). Anomalies of mean DDT values according to weather stations are shown for comparison; Correlation of ALT and $DDT^{1/2}$ for Chukotka and Kamchatka sites (d).

Chukotka (sites R9, R11, R45) (Figure 3(d)), Eastern Chukotka (site R 27 and R 41) (Figure 3(d)) and Kamchatka (Figure 3(e)).

The annual end-of-season observations from sites with long data records within each sub-region were averaged to provide characteristic temporal active-layer trends for each geographic area. The sub-regional trends in active-layer thickness, presented as anomalies from 2005 to 2015 sub-regional ALT mean, along with the annual anomalies in summer (June-August) Degree Days of Thawing (DDT) calculated using air temperature data from the weather stations located within each sub-region, are shown in Figure 4(a,c). To evaluate relations between active-layer thickness and climate, the annual sub-regional thaw depth values were correlated with the square root of annual summer (June-August) DDT (Figure 4(b,d)).

Yana-Indigirka and Kolyma lowlands

Eleven sites are located in the Yana-Indigirka and Kolyma lowlands and represent basins of the Indigirka, Alazeya, and Kolyma rivers. The summer DDT values increase eastward, with Indigirka basin coolest and Kolyma warmest. Maximum values were observed in 2007 (around 1000 for Indigirka-Alazeya and 1400 for Kolyma).

At the single site within the Indigirka basin (site R31) annual thaw depth was monotonically increasing for the first seven years of observation (2004–2010) and reached its maximum of 52 cm in 2010–2011. The second half of the record (2011–2018) is characterized by a monotonic decrease in ALT. The 2018 thaw value of 40 cm is similar to the 39 cm value observed in 2004 (Figures 3(b) and 4(a)).

Such trends cannot be explained by variability in the summer near-surface air temperature; the correlation between DDT and ALT for the Indigirka site is weak (Figure 4(d)).

Two sites representing the Alazeya River basin, located near the village of Andryushkino (R22 and R36), show different trends (Figure 3(b)). These differences are most pronounced over the 2008–2014 period. In 2010 thaw depth at site R36, located within a boggy flood plain covered with dense shrubs, reached a 15-year minimum of 31 cm followed by a monotonic increase over the 2010–2018 period. Simultaneously, at the nearby site R22 representing well-drained southern tundra, thaw depth reached its 15-year maximum of 57 cm followed by four years of monotonic decrease. The positive thaw depth trend at site R 22 become evident over the 2014–2018 period. Annual average thaw depth anomalies observed at the two Alazeya sites show that the active-layer in Alazeya sub-region experienced by gradual thinning over the 2007–2012 period, followed by monotonic thickening. However, just two sites located in drastically different landscapes may not be representative of the broad regional trends. Similar to the situation at the Indigirka site, active-layer thickness does not correlate with summer DDT (Figure 4(d)). For example, thick moss cover, developing in warmer summers can increase the insulating properties of the ground cover and decrease the thawing depth. Moreover, flooding, which is a common phenomenon at R36 site, can contribute to further decoupling between atmospheric climate and the depth of thaw.

The majority (8 out of 11) of observational sites are located in the Kolyma river basin. In this sub-region the sites were established to represent a range of vegetation subzones and landscapes (Table 1). Such diversity in site conditions results in large variability in site-specific long-term thaw depth trends (Figure 3(c)). The trend in sub-regional average active-layer thickness anomalies (Figure 4(a)) indicates that in the Kolyma river basin the active layer has increased by 15 cm over the 1996–2007 period. The high-amplitude changes in annual thaw depth were observed over the 2008–2012 period, followed by relative active-layer stabilization around the long-term mean in the 2013–2018 period. This trend corresponds to observed changes in near-surface air temperature. Figure 4(b) shows a relatively high ($R = 0.6$) correlation between summer DDT and the sub-regional end-of-season thaw depth for the Kolyma River basin.

Chukotka

In general, summer temperatures in the eastern part of Chukotka (Uelen weather station) are considerably lower than in the western part (Anadyr weather station): The accumulated DDT at Uelen is half of that that at Anadyr (Figure 3(a)). However, winter air temperatures are higher in the eastern part, resulting in similar annual average temperatures. At Anadyr, the highest DDT value of 1270 was observed in 2016. At Uelen, the highest DDT of 757 was reached in 2004. The lowest DDT values were observed in the 1990s (700 for Anadyr in 1998–1999; 220 for Uelen in 1995). Both weather stations experienced a gradual increase in DDT values over the 1990–2000 period. However, the DDT trend is complicated by high interannual variability.

In Chukotka all long-term monitoring sites demonstrate a moderate thickening of the active-layer over the period of observation (Figure 3(d)). In western Chukotka (Anadyr Lowland) and eastern Chukotka the mean ALT increases from 2000–2002 to 2016–2018 were 13 and 11 cm, respectively (Figure 4(c)). However, there are some notable differences in ALT trends between two Chukotkan subregions. In western Chukotka (Figure 4(c), and sites R9 and R11 in Figure 3(d)) the rapid monotonic increase in thaw depth, observed between 1998 and 2005 was followed by relative stabilization in the depth of thaw during the 2007–2016 period. In eastern Chukotka (site R27 in Figures 3(d) and 4(c)) the increases in ALT have being consistent through the period of observations. The long-term active-layer trends can be partially explained by the trends in summer DDT. The sites located in Eastern part of Chukotka are characterized by low correlation between ALT and DDT, with R^2 coefficients ranging from 0.3 to 0.6. In the Western Chukotka the correlation coefficients are between ALT and DDT are between 0.7 and 0.9 (Figure 4(d)).

Kamchatka

Climate characteristics for Kamchatka are available from the Klyuchi weather station. The 2003–2018 average of Mean Annual Air Temperature (MAAT) at the Klyuchi weather station is 0.6°C, with a mean summer value of 14.6°C and the corresponding summer DDT value of 1340. Although there is no continuous air temperature data record for the CALM sites, the sporadic observations indicate that the average DDT at CALM sites are significantly lower than at the weather station located at lower elevation. For example, summer DDT for 2012 was 900 at the R30A site, 814 at R30B, and 717 at R30C, compared to 2012 value of 1377 for the weather station. Moreover, the analysis of available temperature data from the CALM sites revealed no correlation with that obtained from the weather station. The ground surface data from site R30C are used as proxy for climate data.

In mountainous terrain, ALT is highly dependent on elevation and slope exposure. The deepest thaw propagation of 80 cm was observed at the site R30A located at the lowest elevation (1300 m a.s.l.). ALT values varied between 67 and 80 cm over the 2003–2012 period for R30A site (Figure 3(e)). Two sites (R30B and R30C) located at 1600 m elevation were established on slopes with different exposure. The range of 2006–2012 ALT values on the southern slope (R30B) was 53–63 cm while only 44–50 cm on the northern slope (R30C). These differences illustrate the effect of topoclimatic factors on annual thaw depth in mountainous terrain.

The site-specific thaw depth records are relatively short for Kamchatka sites. Only one site (R30C) has a record extending to 2018. The available observational data indicate a slight positive trend in the depth of thaw. The highest ALT value was recorded at the R30C site in 2016, which corresponds to the warmest summer during the 2003–2018 period. The deepest ALT for R30A,B was measured in 2009, correspondingly the warmest summer over the 2003–2012 period. Correlation between ALT and summer DDT values is relatively high for the Kamchatka sites (Figure 4(d)). Despite the small increase in annual thaw propagation, several features indicative of permafrost degradation have developed in the vicinity of the R30C observational sites. These include surface subsidence along the northwest border of a cinder plateau and the retreat of the buried ice deposits (see insert and the central part of Figure 2).

Vegetation- and landscape-specific thaw depth trends

The number and locations of sites in the Kolyma-Indigirka lowlands allow examination of thaw depth trends for several vegetation zones and landscape categories representative of the region. Three vegetation zones (Northern Tundra, Southern Tundra, and Northern Taiga) and four landscape categories (Watershed, Yedoma Uplands, Floodplains, and Alases). Long-term trends in summer (July–August) DDT as observed at weather stations located within each vegetation zone is shown in Figure 5(a). The vegetation- and landscape-specific end-of-season thaw depths (Figure 5(b,c)) were obtained by averaging annual values obtained from sites located within specific vegetation zones or landscapes described in Table 1.

Summer DDT trends for all vegetation zones considered for analysis show a consistent pattern: a warming trend for the 1996–2007 period, followed by some stabilization (Figure 5(a)). The summer DDT maximum was reached in 2007 for all three vegetation zones. The latitudinal zonation is evident from Figure 5(a).

The mean summer temperatures averaged for the period of observation is 8.6°C, with corresponding DDT of 800 for typical tundra and 11.7°C with corresponding DDT of 1000 for northern taiga biome.

The depth of thawing follows the latitudinal DDT trend: the coldest typical tundra landscapes have, on average, smaller active-layer thickness. However, the long-term active-layer trends differ between three the vegetation zones (Figure 5(b)). Most notably, the northern taiga sites experienced a much more pronounced increase in thaw propagation over the 1995–2018 period than sites located in taiga biomes. This suggests that the drier sandy soils characteristic of sites located in the northern taiga are more responsive to the increase in summer DDTs (Figure 5(b)).

The positive active-layer trends in relatively dry landscapes are also evident in Figure 5(c). Sites located on well-drained watershed surfaces show a pronounced increase in thaw depth over the 1995–2018 period. These sites have sandy soils with higher thermal conductivity, resulting in greater end-of-season thaw propagation and stronger reactions to increases in summer temperatures. A long-term increase in thaw depth is less notable in the ice-rich Yedoma uplands Figure 5(c). These landscapes have high thermal inertia attributable to latent-heat effects associated with melting ground ice. The poorly-drained sites located on floodplains and in thermokarst depressions (alases) show no discernable long-term active-layer trends (Figure 5(c)). The lack of trend can be explained by latent heat effects associated with high soil moisture content. Relatively thick moss and organic layers, characteristic of those landscapes, also contribute to the stability of the ground thermal regime. However, an abnormal increase in thaw propagation at those sites can occur during floods due to high thermal capacity and conductivity of standing water (Göckede et al., 2017). For example, floods at floodplains sites (R17, R20) in 2004 can be attributed to the significant increases in ALT (Figure 5(c)). Flooding was also evident at the alas site R15A in 2007.

The relations between ALT and DDT for four characteristic landscapes are shown in Figure 6. Moderate correlation coefficients (Pearson product moment correlation) of 0.5 and 0.6 between ALT and cumulative DDT were found for sites located on watersheds and alases. The slope of lines in Figure 6 also indicates that the well-drained watershed sites have the highest sensitivity to atmospheric forcing. The low correlation values characteristic of floodplain sites ($R = 0.2$) can be attributed to periodic flooding, which decouples the ground thermal regime form the atmospheric climate. Similarly, the high thermal inertial

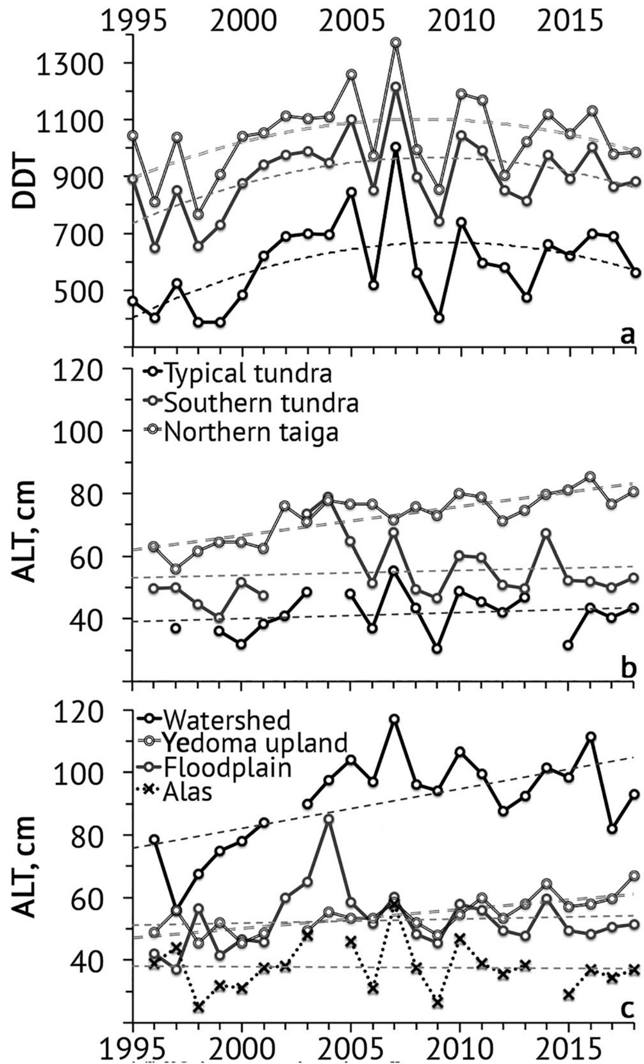

Figure 5. DDT (JJA, a) dynamics in different vegetation zones of the Kolyma region in comparison with ALT dynamics, averaged according to vegetation (b) and mesorelief (c) settings. Linear or polynomial (2nd order) trends are shown by dashed lines. Typical tundra represented by Ambarchik, southern tundra by Kolymskaya, and northern taiga by Chersky stations climate data. Mean ALT values for all sites in selected area (according to Table 1) were used.

associated with high ground ice content and the latent heat of phase change results in low correlation ($R^2 = 0.3$) between ALT and DDT for Yedoma sites (Figure 6).

Although vegetation- and landscape-specific differences in thaw depth trends and relations to atmospheric climate can be illustrated by this analysis, the pronounced heterogeneity of edaphic conditions within the Kolyma-Indigirka lowlands (i.e. soils, vegetation, soil moisture) and the small number of representative sites precludes us from regional extrapolation. Moreover, we recommend caution using CALM data from East Siberia to make extrapolations and/or predictions of active-layer changes until the spatial variability in land-cover and lithological composition is represented adequately.

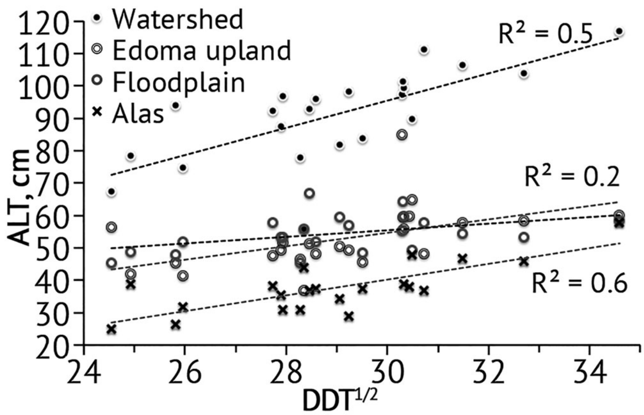

Figure 6. Correlation of ALT and $DDT^{1/2}$ for different mesorelief settings at Kolyma area.

Conclusions

Analysis of 20 years of observations conducted in East Siberia and the Russian Far East under the auspices of the Circumpolar Active Layer Monitoring (CALM) program indicates that the regions are characterized by a general thickening of the active layer in response to increasing air temperatures. Measurements at weather stations indicate that the summer air temperature trend is consistent for most of the region, with the exception of Kamchatka. DDT values increased until 2007, followed by stabilization in later years. The relatively fast increase in thaw depth observed in the 1990s and early 2000s has slowed significantly over the last 10 years. This decrease in the active-layer thickening trend is consistent with summer air temperature trends. The stabilization in thaw propagations observed in recent years can also be attributed to the fact that the active layer propagated into the ice-rich transient permafrost layers. As a result, heat is expended on melting the ice resulting in slowing the thickening of the active-layer. However, more detailed investigations are needed to evaluate this effect. The overall increase in the annual ALT relative to the mean over the observation period is within the 10–12 cm range for the Indigirka-Kolyma region and Chukotka, and around 5 cm for Kamchatka. Well-drained sites with sandy soils have higher thaw propagation and react to atmospheric climate faster than sites with finer-textured soils.

The active-layer response to summer air temperature fluctuations is controlled mainly by soil lithology, water/ice content, and the thickness of the vegetation layer and organic/peat horizons. As a result, interannual variations in the end-of-season thaw depth reflect not just air temperature fluctuations, but also complex interactions between various components of the Arctic ecosystem. For example, higher air temperature might contribute to enhanced growth of moss, which in turn could increase the insulative properties of vegetation and result in a decrease in thaw propagation in warmer summers. Lower precipitation during warmer summers could result in lower thermal conductivity of the soil, mitigating the effect of increased air temperature on thaw propagation. Such effects could not be fully addressed within the framework of this study describing generalized thaw depth trends over a very broad geographic region. More detailed site-specific investigations are needed to evaluate ecosystem effects on active-layer thickness.

It should be noted that the absolute values of active-layer thickness reported here should be treated with caution. As indicated in the methodology section of this report, simultaneous measurements at all the sites would not be possible due to logistical constraints. This report presents raw, observed end-of season thaw depth data that were not subjected to calibration procedures, such as those employed for the Kolyma sites by Fyodorov-Davydov et al. (2004) and for Chukotka by Zamolodchikov et al. (2004). The only exception is the R18 site, where measurements were made annually at the very end of the thawing season, when freezing started in the Fall. For the Indigirka-Kolyma region, comparison of direct end-of-season thaw depth observations conducted in mid to late August with maximum values of active-layer thickness achieved in the first 10 days of September indicate the average difference between two value to be 2–4% (Fyodorov-Davydov et al., 2004). For Chukotka, the difference between the maximum active-layer thickness achieved in late September - early October and the CALM measurements conducted in late August – early September can be as much as 5–6% (Zamolodchikov et al., 2004). For the Kamchatka sites, the maximum difference between ALT and CALM measurements is on the order of 5%. These differences should be considered if the data reported here are used for validating models used to estimate ALT. Our next step is to use ground temperature verification from year-round monitoring in boreholes to create a calibration curve for each site. However, these limitations do not affect the temporal trends of ALT change reported in this study.

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