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Thermal regime of Cryosols and underlying permafrost in North Yakutia in the context of global climate change

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Abstract. The warming and an increase in the amount of solid precipitation, which became apparent in North Yakutia on the threshold of the 21[st] century, have led to an increase of soil temperature in winter season and of the permafrost. The heat fluxes measured in the taiga soil on the Kolyma Lowland reveal an imbalance in the annual heat gain and loss in the cryogenic ecosystem amounting to 26.3–56.1% of the incoming energy. An increase in the summer air temperatures of the 2000[th] caused a universal increase in the depth of seasonal soil thawing. After the drop in high summer temperatures, the active layer thickness (ALT) either continued to grow or stabilized at higher levels in the watershed ecosystems of the Kolyma Lowland; however, ALT returned to its initial values in the tundra of the Yana-Indigirka Lowland. As for the floodplain landscapes, ALT increased near-linearly over the 24 years of monitoring. The waterlogged tundra and taiga soils as well as the upland gleyzem of the Bykovsky Peninsula differed only by a temporary increase in the thawing depth. The degree of the soil and permafrost thermal regime transformation tends to increase from west to east, fitting the heterogeneity of climate changes.

1. Introduction

The global warming, which commenced in the cryolithozone of the North Hemisphere in the second half of the 1960s, has involved to a most considerable degree in West Siberia [1], Central Yakutia [2], north-west part of North America [3], and several other regions. A considerably deeper seasonal thawing of permafrost-affected soils is observed during the last decades at the Marre-Sale [4], Nadym [5], and Vorkuta [6] observation sites. A significant increase in the permafrost temperature is recorded in West

Siberia [5, 7], Bolshezemelskaya tundra [8], and in North America [9]. A partial degradation of permafrost [8] or the transformation of merging permafrost to non-merging one [7] is recorded. Further deepening of the active layer and a decrease in the area of permafrost [10, 11] are predicted.

The climate warming appears as an increase in the air temperature, first and foremost, during cold seasons [12]. The thermal regime of northern permafrost-affected soils also mainly changes at the expense of the winter component. The dynamics of positive soil temperatures on the background of global warming may also manifest itself in different ways; in particular, a decrease in the summer temperature was observable in several regions because of increased precipitation [13].

Characteristic of North Yakutia's climate at the beginning of the 21st century was a weak and very weak increase in air temperature [7]. Analysis of the data of a few weather stations on the coast does not show any significant increase in soil temperature during 1969–1990 [14]. Our monitoring in North Yakutia commenced later, in the mid-1990s. The data accumulated over almost a quarter century require analysis and generalization, in particular, in order to find out the response of cryogenic soils and permafrost to global climate change in this yet poorly studied region.

2. Objects of monitoring; research plan and methods

The study was mainly conducted under the Circumpolar Active Layer Monitoring (CALM; https://www2.gwu.edu/~calm/) and Thermal State of Permafrost (TSP; https://ipa.arcticportal.org/products/gtn-p/tsp) projects in the Kolyma and Yana-Indigirka Lowlands (Yakutian Coastal Lowlands) and Bykovsky Peninsula, which separates the mouth of a Lena River branch and Tiksi Bay (figure 1). The studies covered both tundra landscapes and northern taiga subzone. The soil types are given according to the standard Russian classification [15] with parenthesized WRB names [16].

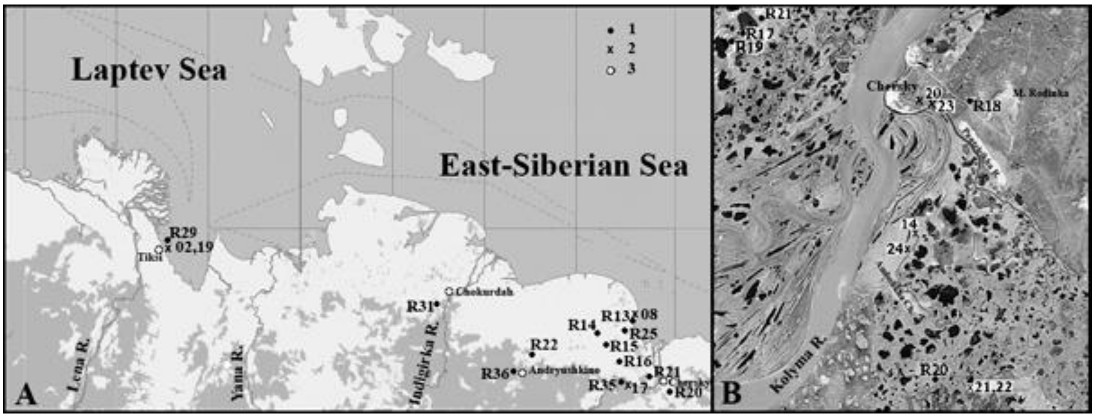

Figure 1. Scheme of the monitoring sites (A) over the all examined area and (B) in the Kolyma River lower reaches: (1) sites for measuring ALT (CALM)R13 – Maliy Chukochiy Cape (edoma and alas), R14 – Bolshaya Chukochya River, R15 Malaya Kon'kovaya River (edoma and alas), R16 – Segodnya Pingo, R17 – Akhmelo River, R18 – Rodinka Mountain, R19 – Glukhoe Lake, R20 – Malchikovskaya Channel, R21 – Akhmelo Lake, R22 – Alazeya River, R25 – Yakutskoe Lake, R29 – Bykovsky Peninsula (edoma and alas), R31 – Allaiha River, R35 – OmolonRiver, R36 – Andryushkino Village; (2) thermometric boreholes (TSP); and (3) weather stations (the last two digits of the TSP borehole numbers are shown).

According to the CALM protocol, the active layer thickness (ALT) is measured with a metal rod on standard (100 × 100 m) plots with an interval of 10 m. The watersheds situated on the examined area are in most cases formed by ice-rich silt loamy sediments of the Upper Pleistocene yedoma suite [17] and are referred to as "yedomas". They alternate with thermokarst depressions, alases, formed as a result of the Holocene warming. The zonal soils of watersheds within the tundra zone are represented by different subtypes of cryozems (Turbic Glacic Cryosols) and gleyzems (Reductaquic Turbic Glacic Cryosols). Various gleyzems (Reductaquic Glacic Cryosols), peat gleyzems (Histic Reductaquic Glacic

Cryosols), and peat soils (Cryic Histosols) are abundant in the polygonal bogs of alases. Seven CALM sites (R13, R14, R15B, R22, R25, R29A, and R31) characterized the landscapes of yedoma watersheds. Site R25 is situated on a steep (20–27°) slope exposed to the southeast and the remaining sites, on near-horizontal surfaces or gentle slopes. The ALT in alases was measured at points R29B, R13A, and R15A.

Cryometamorphic soils (Turbic Cryosols) are prevalent on the watersheds of northern taiga subzone. This landscape was characterized according to site R18. As for boggy forests (R35 and R36), gleyzems (Reductaquic Turbic Cryosols), peat gleyzems (Histic Reductaquic Turbic Cryosols), cryozems (Oxyaquic Turbic Glacic Cryosols), and peat cryozems (Folic Oxyaquic Turbic Glacic Cryosols) were prevalent there. A similarity of the soil-forming rock simplifies the comparison of the soil thermal regime over the entire examined territory except for the Khallerchinskaya tundra, a comparatively small area in the northeast of the Kolyma Lowland formed by fine and very fine sands. Characteristic of this area in general is the prevalence of polygonal bogs. Zonal tundra communities and the corresponding podzolized podburs (Spodic Turbic Cryosols), are relatively abundant in the southern, most drained, part of the Khallerchinskaya tundra (R21) and are observed as small islands among bogs (R16) in the remaining part of this territory. In the southeastern part of the sandy area, tundra communities are replaced by larch open forests (R19) with abundant podzolized podburs.

The floodplains, examined within the northern taiga subzone, display a high facial heterogeneity. In the R17 and R20 sites, drained near-flow areas with alluvial humic gley soils (Reductaquic Turbic Glacic Cryosols) alternate with bog facies with alluvial peat gley soils (Histic Reductaquic Glacic Cryosols).

Of the 18 sites with additional observation series, 15 sites in the Kolyma Lowland have been examined in 1996–2007. As for the Yana-Indigirka Lowland, the observations continue since 2004 (R31) and in the Bykovsky Peninsula (R29), since 2003.

Soil temperature was measured on positive elements of nanorelief at a number of the active layer monitoring sites with data loggers (Thermologgers Onset HOBO and StowAway, United States), allowing for an accuracy of ±0.2–0.4 °C; usually, the records were made with an interval of 2 h. The temperature data series in our study are shorter than for ALT data series; correspondingly, it was more reliable to use ALT as an integral characteristic of the thermal state when studying the dynamics of summer thermal regime of soils.

A continuous **temperature monitoring of the permafrost** in North Yakutia was commenced in 2006, while the earlier data were sporadic. The boreholes were equipped with four-channel HOBO U12 data loggers with TMC-HD thermistors (measurement accuracy, ±0.2 °C; resolution, 0.004 °C). Currently, the monitoring is in progress in 10 thermometric boreholes with a depth of down to 25 m. In some cases, boreholes are directly adjacent to the points for ALT measurement. In the basin of the Kolyma River lower reaches, boreholes RU06-0014, RU06-0021, and RU06-0024 characterize the permafrost of the floodplain of the Ambolikha Channel of Kolyma River; RU06-0020 and RU06-0022, of yedomas; and RU06-0023, of the alas (figure 1b).

The heat fluxes were studied in the profile of northern taiga cryometamorphic light loamy soil of a gentle (4–5°) southern slope near the Chersky (R18D, east of the Kolyma Lowland) since the fall of 2014. DTP–0924 heat flux probes equipped with analog-to-digital signal converters and an LDD–1/100 (Joint Stock Company "Research and Production Enterprise" ETALON, Omsk, Russia) data logger were used for observations. The sensors were installed into the soil profile at depths of 0 (under the vegetation cover), 40, and 85 cm (bottom of the active layer).

In data processing, the change in parameters was assessed according to linear trends. In addition, polynomial functions mainly of the fourth and fifth degrees were used, which allowed the satisfactory approximating dependences to be obtained.

3. Climate of North Yakutia

The climate of North Yakutia can be characterized using the data of four weather stations – Chersky, Andryushkino, Chokurdah, and Tiksi. The mean annual air temperature over 1980–2019 (for the Andryushkino station, only the data since 1996 were available) in the examined area was –12.8 to –10.3 °C. The mean temperature of July varied from 8.2 to 13.0 °C and of January, from –34.1 to –30.2 °C.

The winter seasons are regarded as severe. The continentality according to Ivanov amounts to 163 – 200. According to the amount of precipitation, the climate is semidry with prevalence of summer precipitation.

The data of the Chersky, Andryushkino, and Chokurdah stations demonstrate an increase in summer temperatures in 1990–2000; the linear trend values of the annual sums of mean monthly air temperatures over 0 °C during this period amounted to 1.07, 1.19, and 0.68 °C/year, respectively (coefficients of determination, R^2, were 0.32–0.63). This was followed by a certain decrease in summer temperatures in the 2010s followed by the trend of a new warming. The data of the Tiksi weather station demonstrate a smooth growth (0.35 °C/year) in the sums of mean monthly positive air temperatures starting from the second half of the 1980s to the mid2010s followed by a decrease in this parameter.

Positive trend values of the sum of mean monthly air temperatures below 0 °C were 0.82 and 1.49 °C/year according to the Chersky and Andryushkino stations, respectively (R^2 = 0.39–0.49); note that the maximum growth in winter temperatures was recorded since the end of the 1990s to the second half of the 2010s. In Chokurdah, the sums of negative temperatures increased only since the end of the 1990s with a trend of 1.22 °C/year (R^2 = 0.45). As for the Tiksi station, the warming was recorded even later, since the first half of the 2000s to the mid-2010s with a trend of 1.99 °C/year (R^2 = 0.50).

Thus, an increase in the air temperature at the Kolyma Lowland was somewhat more pronounced as compared with more western regions, which was especially characteristic for the summer season. In addition, the trend of a delay in the maximum of summer temperatures from east to west was observable: the warming in the Kolyma Lowland continued to 2007; in the Yana-Indigirka Lowland, to 2010; and in the region of the Lena River mouth, to 2015. An increase in the winter temperatures in Tiksi also commenced approximately by 5 years later and was shorter as compared with the Coastal Lowlands.

The amount of winter precipitation in the Yakutian Coastal Lowlands displayed the trend of an increase since the mid-1980s; the linear trend values amounted to 2.00 and 2.43 mm/year (R^2 = 0.26–0.45) according to the data of the Chersky and Chokurdah stations, respectively. The period of the most intensive increase in Chersky (3.59 mm/year) was recorded in the early 2000s. Note also that three abnormally snowy winters were observed in a row in the Yakutian Coastal Lowlands in 2015–2016, 2016–2017, and 2017–2018; the maximum snow depth of 72–93, 73–94, and 106–180 cm, respectively, was recorded at the Chersky, Andryushkino, and Chokurdah weather stations. On the contrary, the amount of solid precipitation in Tiksi in the 2010s decreased; nonetheless, the maximum snow cover in the winter of 2016–2017 was rather high, reaching 30 cm versus 6–14 cm, characteristic for the last decade.

4. Dynamics of soil temperature in winter season

The increases in winter air temperatures and the amount of solid precipitation influence the dynamics of negative soil temperatures in North Yakutia. An increase in the soil temperature during the cold season was observed at all sites of long-term temperature monitoring (R13, R14, R18, R18C, R21, R22, R29A, and R31). The polynomial functions approximating the dynamic of annual sums of negative mean daily temperatures at a depth of 20 or 50 cm (R^2 = 0.61–1.00) reveal wave-like fluctuations superimposed on a linear trend (figure 2). The first period of warming corresponds to the increase in winter temperatures in the 2000s and the second one, to the mid–late 2010s and is likely to be primarily associated with the increase in winter precipitation. The annual sums of negative temperatures minimal in the absolute values in the Coastal Lowlands were in all cases observable in 2015–2018 with their snowiest winters. This dynamics in the Kolyma Lowland appeared earlier and the abnormally winter precipitation of the last years only reinforced the general trend (figure 2a–d); however, the positive trend recorded in the Yana-Indigirka Lowland (R31) and Bykovsky Peninsula (R29A) over the observation period emerged owing to the recent snowy winters (figure 2e, f). The least manifestation of winter warming in the case of the gleyzems of the Bykovsky Peninsula agrees well with a less pronounced increase in the air temperature and a decrease in the solid precipitation in this area.

The prolongation of the fall zero curtain period in the active layer in the second half of the 2010s was most pronounced in northern taiga, with better conditions for snow accumulation. In the profile of cryometamorphic light loamy soil (R18D), typically freezing by mid-January, the merging of seasonal frost and permafrost zones in abnormally snowy winters at the end of February–middle of March; thus, no more than 2 months remained for the freezing of soil profile.

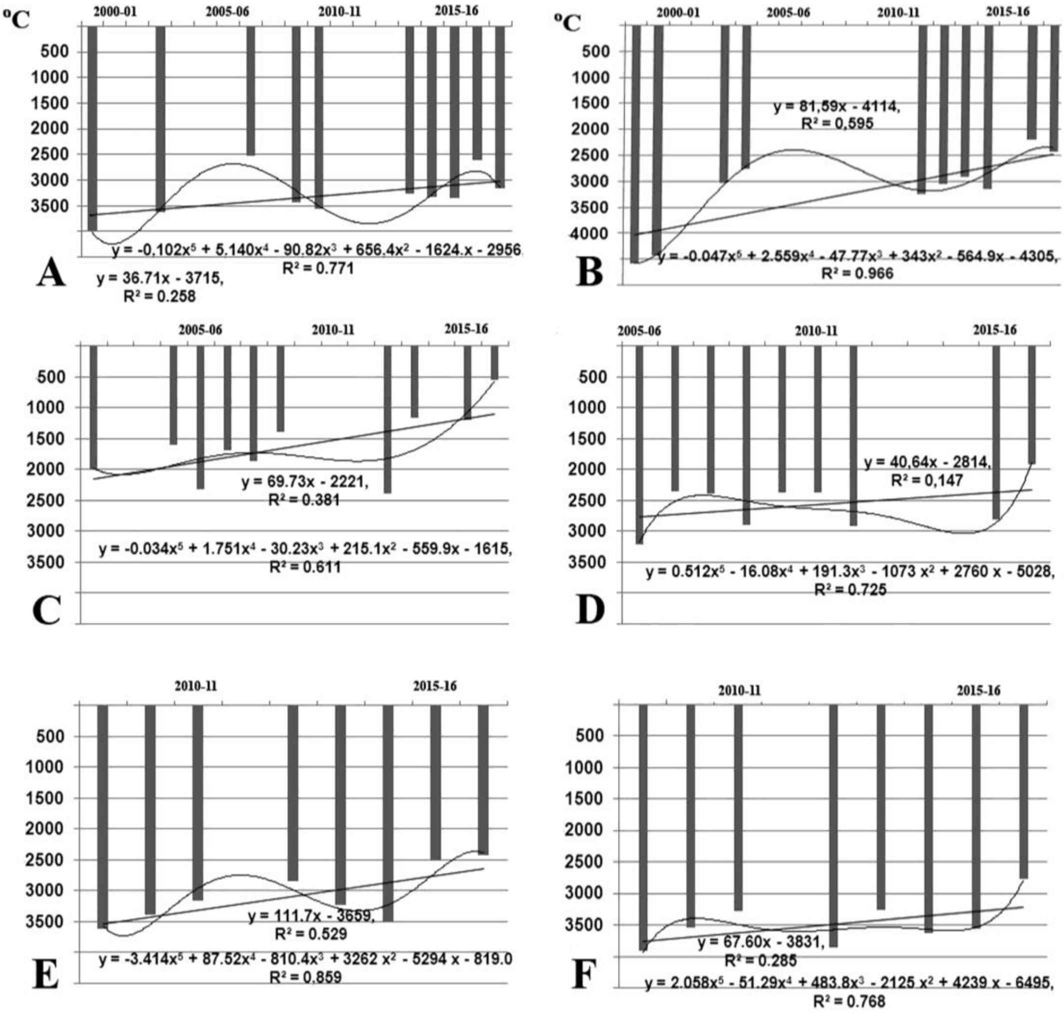

Figure 2. Long-term dynamics of the annual sum of mean daily negative soil temperatures: A – R13 (20 cm), B – R14 (20 cm), C – R21 (50 cm), D – R22 (50 cm), E – R31 (20 cm), F – R29A (20 cm).

5. Heat fluxes and heatturn in the cryogenic soil–permafrost system

The study of the heat fluxes in soil profiles gives a better insight into the mechanism underlying the growth of winter soil temperatures in the course of global warming. The annual input of heat energy to the cryogenic soil–permafrost system over 5 years of monitoring was 136.29–172.21 MJ/m^2, with 19.7–28.0% of this amount spent for heating the permafrost during the warm season. The remaining 72.0–80.3% (99.32–121.57 MJ/m^2) were spent for heating the active layer and the ice–water transition there. The annual heat loss in winter season amounted to 66.50–124.96 MJ/m^2 and was minimal in the snowiest winter of 2017–2018 and maximal in the winter of 2018–2019, with relatively little snow.

A positive heat balance in this system in different years was 44.55–87.42 MJ/m^2 (26.3–56.1% of the total energy input), comprising 24.83–60.31 MJ/m^2 (22.2–52.7%) for the active layer and 13.89–33.28 MJ/m^2 (37.6–88.3%) for permafrost.

The shift in energy balance is first and foremost determined by a decrease in the negative (winter) component of the annual heatturns. The resulting imbalance leads to warming of the permafrost, which becomes an accumulator of heat energy in the cryogenic ecosystem.

6. Permafrost temperature dynamics

By the beginning of monitoring, the permafrost temperature in North Yakutia varied from –11 °C (Bykovsky Peninsula) to –3…–6 °C (taiga and floodplain landscapes in the east of the Kolyma Lowland).

A comparison of the current monitoring data and the sporadic measurements of 40 years ago made in the Kolyma Lowland suggests that the permafrost temperature in the examined area has grown by 1.5–2.0 °C. In this process, a significant warming there commenced only in the 2000s, when the maximum increase in winter air temperatures was recorded. Before 2015, a stable increase in the permafrost temperature was observed varying in its rate in the tundra zone from 0.07 °C/year in the Bykovsky Peninsula to 0.11 °C/year in the Kolyma Lowland and amounting to 0.06–0.07 °C/year in the taiga zone.

The increase in the winter precipitation in the second half of the 2010s resulted in a drastic rise in the permafrost temperature in the Kolyma Lowland, which initially appeared in the northern taiga, where the linear trend values elevated to 0.18–0.40 °C/year. The rate of the temperature increase in floodplain sites, where the permafrost was known for its thermal stability, during this period reached 0.26–0.29 °C/year. Here, the rock below annual temperature fluctuations layer warmed on the average by 1 °C over several years.

7. Active layer thickness dynamics

When studying the dynamics of soil thermal state in warm season, it is reasonable to divide the overall observation data series into two periods, namely, the period of an increase in the summer air temperatures (warming period) and the period of unstable summer temperatures (period after warming). At the first stage of monitoring, an increase in the ALT was observed in most of the examined landscapes of North Yakutia (table 1), including the ecosystems displaying no correlation between the soil thawing depth and summer meteorological data (R17, R20, and R31). The maximum ALT growth rate during this period, amounting to 3.79 cm/year (R^2 = 0.77), was observed on a steep slope of a tundra yedoma in the region of the Yakutskoe Lake (R25). High rates of the increase in seasonal thawing depth, amounting to 2.59–3.39 cm/year (R^2 = 0.47–0.77), were also observable in the sandy soils of the Khallerchinskaya tundra (R16 and R21) and the adjacent open forest (R19), which is associated with their good draining conditions and high thermal conductivity.

In general, characteristic of all observation sites over the all monitoring period (1996–2019) were positive values of the trends except for two alases, R15A and R29B (table 1). The highest rates of an increase in the thawing depth were observed in sandy profiles (0.93–1.28 cm/year; R^2 = 0.32–0.53) followed by alluvial varieties (0.67–0.72 cm/year; R^2 = 0.54–0.60) and zonal cryometamorphic soil of taiga ecosystem (0.52 cm/year; R^2 = 0.42). The data approximation with polynomial functions illustratively demonstrates the types of response of the active layer to climate changes (figure 3).

The ALT in the zonal taiga biogeocenoses (R18) fluctuates on the background of a well pronounced positive trend (figure 3a). In the second half of the 2010s, the ascending branch of the last fluctuation cycle in its scale already exceeded the record of 2007, the year of the summer thermal maximum.

A drastic increase in the sandy soil thawing depth (R16, R19, and R21) during the warming period was replaced by its stabilization at a new level, which exceeded the initial one by 27–28 cm, which is maintained for a long time (12 years) after the drop of high summer temperatures (figure 3b).

The long-term ALT dynamics in the zonal tundra ecosystems of the yedomas in the Coastal Lowlands is heterogeneous. The patterns observed in sites R14 and R22 were similar to the dynamics for zonal taiga described above, with the same maximums and minimums (figure 3c). As for sites R13 and R15B, an increase in the ALT during the period of warming was followed by a decrease and, after 6–7 years, stabilization at the level exceeding the initial one by 5–8 cm (figure 3d). The third type was observed in site R31, where the period of growth in ALT was replaced since 2011 by the period of decrease, which drew ALT back to its initial value (figure 3e). Presumably, this is associated with a less pronounced warming in the Yana-Indigirka Lowland as compared with the Kolyma Lowland.

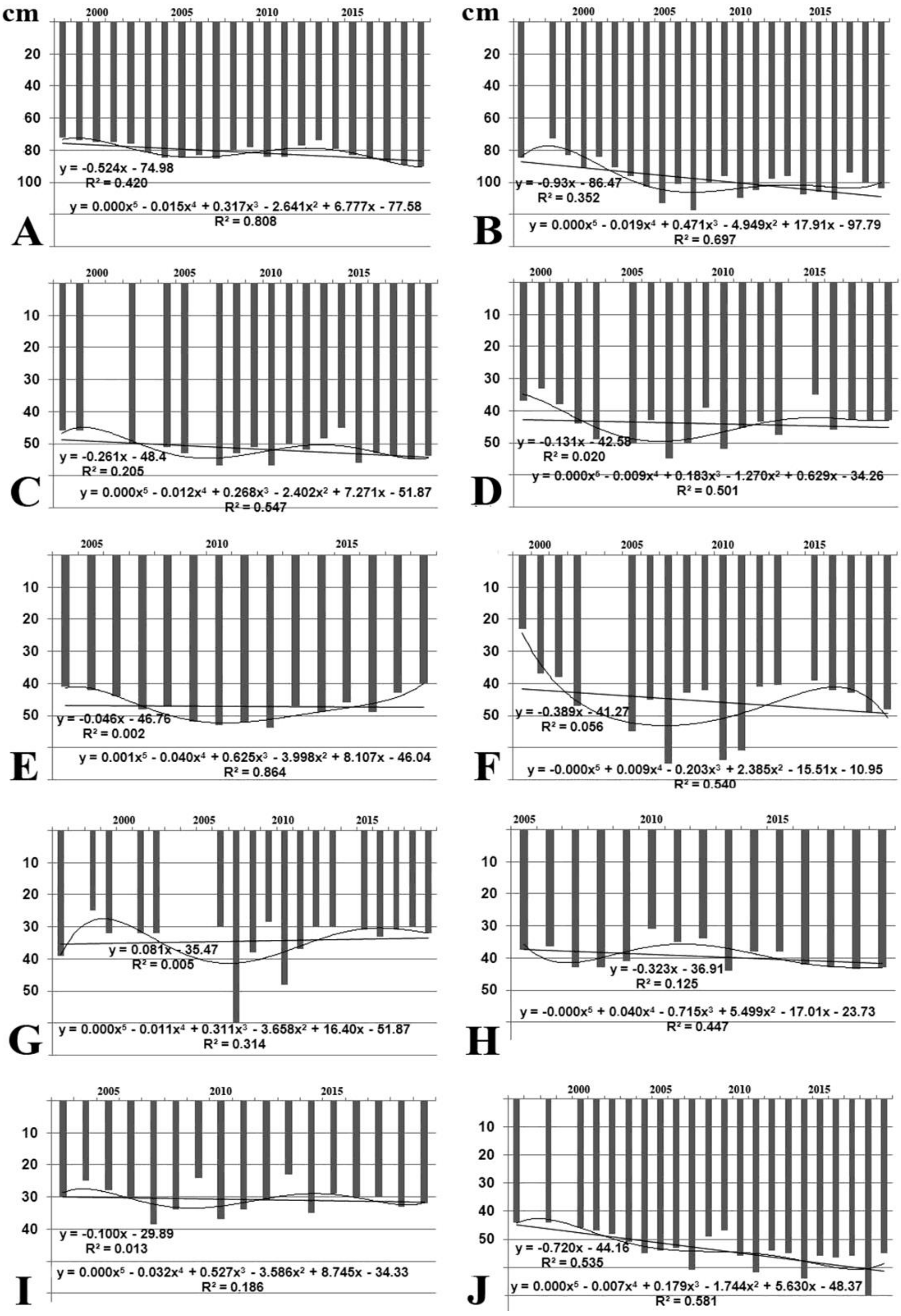

Figure 3. Long-term dynamics of the mean ALT: A – R18, B – R21, C – R22, D – R13, E – R31, F – R25, G – R15A, H – R36, I – R29A, J – R17.

The inertia of tundra watershed biogeocenoses can be associated with the presence of ice-rich self-reproducing cover horizon topping the profile of the yedoma suite and underlying the active layer. Because of a buffering role of this horizon, the trends of thawing depths of the tundra cryozems during the all observation period are, as a rule, low and statistically insignificant (table 1). The changes in ALT had the maximum amplitude on a dry and well warmed slope (R25), lacking the cover horizon (figure 3f). The fluctuations distinctly repeated the dynamics of summer air temperatures without a statistically significant long-term trend.

Table 1. Rates of the increase in soil ALT (cm/year) in long-term dynamics (linear trends).

Sites	Over the summer warming period		Over the all monitoring period (1996–2019)	
	cm/year	R^2	cm/year	R^2
R13	2.13	0.69	0.13	0.02
R13A	1.87	0.30	0.09	0.01
R14	0.53	0.39	0.29	0.32
R15A	1.37	0.24	-0.09	0.01
R15B	1.90	0.82	0.05	0.0
R16	2.59	0.47	0.99	0.32
R17	1.44	0.85	0.72	0.54
R18	1.64	0.88	0.52	0.42
R19	3.09	0.77	1.28	0.53
R20	0.28	0.09	0.67	0.60
R21	3.39	0.77	0.93	0.35
R22	1.18	0.95	0.26	0.21
R25	3.79	0.77	0.39	0.06
R35	–	–	0.16	0.02
R36	2.75	0.62	0.26	0.12
R31	2.11	0.95	0.05	0.00
R29A	0.12	0.01	0.10	0.01
R29B	-0.26	0.03	0.03	0.00

The waterlogged terrains – alases (R13A, R15A, and R29B; figure 3g) and bogged open forest (R35 and R36; figure 3h), with their characteristic large moss projective cover and thick organogenic horizons in soil profiles – also did not display any directed changes in ALT over the period of monitoring. The dynamics there is approximated with the functions that describe the fluctuations around a near-zero or a statistically insignificant trend. The dynamics of a similar type was also characteristic of the zonal ecosystem in the Bykovsky Peninsula (R29A; figure 3i). A high degree of soil hydromorphism and the prevalence of mosses in the plant cover are combined there with a weakly pronounced increase in the summer temperatures.

Finally, the increase in ALT over the period of monitoring in the R17 and R20 floodplain landscapes to the maximum degree approached a linear form (R^2 = 0.58–0.74; figure 3j).

A relatively weak correlation (r = 0.51–0.78) or the absence of any correlation between the ALT and summer air temperatures in the presence of long-term positive trends for this parameter, a successive year by year increase in the soil thawing depth during warming period on the background of close mean summer air temperatures, and continuing increase in ALT or its stabilization at a higher level as compared with the initial value in some sites after a drop in the high summer temperatures suggest that ALT is frequently determined not only by the weather conditions of a present summer season, but also by more general climatic patterns. On disturbance of equilibrium as a result of long-term warming, the inertial cryogenic soil–permafrost system fails to automatically restore its initial state in the case of a temporary decrease in summer temperatures in many, first and foremost, genetically autonomous biogeocenoses. The process of an increase in the soil thawing depth can acquire its own inertia most likely determined by growth of the permafrost temperature (heat accumulation in cryogenic ecosystem) and, in the case of yedoma remnants, presumably also determined by a partial degradation of the buffering cover horizon caused by climate change.

A close to linear growth in the thawing depth of alluvial soils in the absence of any correlation with summer temperatures (r = 0.11–0.49) is the most difficult to interpret. This is unexplainable with the accumulation of heat energy by the permafrost component of ecosystem since the increase in soil temperature in this case commenced only recently as a result of abnormal winter snowiness, whereas the increase in ALT continues for 24 years. Presumably, this increase is associated with certain changes in the hydrological regime of this region, also resulting from global warming.

8. Conclusions

(1) Global warming has caused an imbalance between the annual gain and loss of heat energy in the soils of North Yakutia; this imbalance drastically increases in the years with abnormally snowy winters. The excess energy is accumulated, in particular, in the permafrost, causing its warming.

(2) The temperature of permafrost commenced to increase on the threshold of the 21st century with the mean trends of 0.07–0.11 °C/year in the tundra zone and 0.06–0.07 °C/year in the taiga zone. Since 2016, the rates of temperature elevation have increased owing to a high amount of solid precipitation, which to the highest degree appeared in the landscapes of northern taiga subzone (0.18–0.40 °C/year), with its better snow accumulation.

(3) The increase in soil temperature in cold season was characteristic of the entire North Yakutia; however, this trend long ago appeared in the Kolyma Lowland versus the examined sites of the Yana-Indigirka Lowland and Bykovsky Peninsula, where a positive trend of the annual sums of mean daily negative temperatures became evident only recently.

(4) The increase in summer air temperatures observed in the 2000s caused a universal growth in ALT thickness in the landscapes of Yakutian Coastal Lowlands. In the period after warming, the seasonal thawing depth of the Kolyma Lowland autonomous soils either stabilized at a new level or continued to grow, while the thawing depth in the Yana-Indigirka Lowland tundra soil restored its initial value. The floodplain landscapes displayed an almost linear growth in the ALT over the period of monitoring. Characteristic of the waterlogged taiga and tundra soils as well as of the upland gleyzems of the Bykovsky Peninsula was a temporary increase in the thawing depth. Most likely, an increase in the permafrost temperature enhances stabilization or further increase in ALT after the drop in high summer air thermal characteristics and the changes in hydrological regime, also associated with global warming, correspondingly act at the floodplains.

(5) Both climate changes and the corresponding response of cryogenic ecosystems are more pronounced in the subarctic part of North Yakutia as compared with its arctic area (Bykovsky Peninsula). Within the examined region, the degree of transformation of soil and permafrost thermal regime has the trend of an increase from west to east.

Acknowledgments

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