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THE TEMPERATURE REGIME OF SOILS IN NORTHERN YAKUTIA

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Soil profiles in Northern Yakutia differ in average duration of the season of positive temperatures, the difference being 2.3 times between soil types and 1.8 between zonal loam soils, at a depth of 20 cm. The seasons of >0 °C and >5 °C soil temperatures may be shorter in wetter boggy areas with thicker organic horizons. The durations of fall freezing and persistent near-zero temperatures vary from 1–2 months for tundra cryozem and gleyzem (turbic glacic cryosols) to 2.5–3.5 months for taiga cryometamorphic soils (cambic turbic cryosols), organic cryozem (folic cryosol), and tundra podburs (spodic turbic cryosols). The active layer freezes mostly from above (top to base), except some years of cool summers in the tundra zone when it freezes partly from below. The tundra and taiga soils show a warming trend of the soil climate since the late 1990s dynamics according to annual freezing degree-day sums. The soils of Northern Yakutia vary in total heat spent on active layer thawing $Q_{t>0}$, the difference reaching 10 times.

Soil temperature regime, soil climate change, active layer, freezing of active layer from above and from below, near-zero temperatures, zero curtain, Northern Yakutia

INTRODUCTION

In our previous paper [*Fedorov-Davydov et al., 2018*], we characterized the soils of northern Yakutia in terms of annual and seasonal (summer) mean temperatures, as well as mean monthly temperatures for the warmest and coldest months. The thermal state of soil was found out to vary as a function of geography, topography, lithology, plant communities, and soil properties. This paper addresses the seasonal and long-term variations in temperature patterns of soil profiles at the same sites.

OBJECTS AND METHODS

The study region, its soils, and the methods of temperature measurements were described in [*Fedorov-Davydov et al., 2018*]. For periods of monitoring see Table 2 in the cited paper. Temperature measurements in soil profiles allowed mapping the thawing and freezing dynamics in the region.

Soil temperatures may remain fluctuating about zero (from –0.5 to 0.5 °C) for months on transitions from spring to summer and fall to winter, and the duration of this period should be estimated separately when calculating the lengths of positive and negative temperature seasons. The temperatures around –0.5 to 0.5 °C in soil profiles result from alternating freezing and thawing of soil moisture and latent heat release, which interferes with heat transfer. This effect (*zero curtain*) and the respective periods of different durations depending on depth should be taken into consideration.

The thermal state of soils was estimated using the heat parameter $Q_{t>0}$, in kcal/(m^2·yr) [*Makeev and Ostroumov, 1986*], which measures the amount of heat spent on warming the soil from 0 °C to its maximum temperature and is found as part of the annual freezing-thawing cycle as

$$Q_{t>0} = C\sum_{i_0}^{i_n} t_{\max}\left(h_{i+1} - h_i\right),$$

where C is the heat capacity, kcal/(m^3·°C); $t_{\max}$ is the maximum mean daily soil temperature over a year in the layer i, °C; h is the depth, m; the subscript i corresponds to the soil layer number; i_0 denotes the surface layer; i_n is the soil layer with the maximum temperature 0 °C (active layer base).

The $Q_{t>0}$ parameter was estimated using maximum daily means as raw data and points on envelope curves of temperature variations in the annual freezing-thawing cycle to compensate for data which are inevitably lost during automatic temperature acquisition. The $t_{\max}$ envelope curves were plotted by second-order exponential approximation of the measured values (Fig. 1). The area between the 0 °C line and the $t_{\max}$ envelope is proportional to $Q_{t>0}$.

The misfit between the measured and calculated values does not exceed rms error in measurements at observation sites (Fig. 1). The sets of t_{max} data found from the envelopes are free from gaps, unlike the monitoring datasets, and are thus applicable to estimate the temperature distribution, in the same way as the directly measured temperatures.

The $Q_{t>0}$ estimates based on envelope curves are suitable for both analyzing time series and comparing soil profiles. The $Q_{t>0}$ values for loam and sand (R16 and R21) soils were calculated with assumed heat capacities of 900 kcal/(m^3·°C) and 700 kcal/(m^3·°C), respectively, which correspond to common values for unfrozen soil [*Yershov et al., 1984; Zharikova, 1989*].

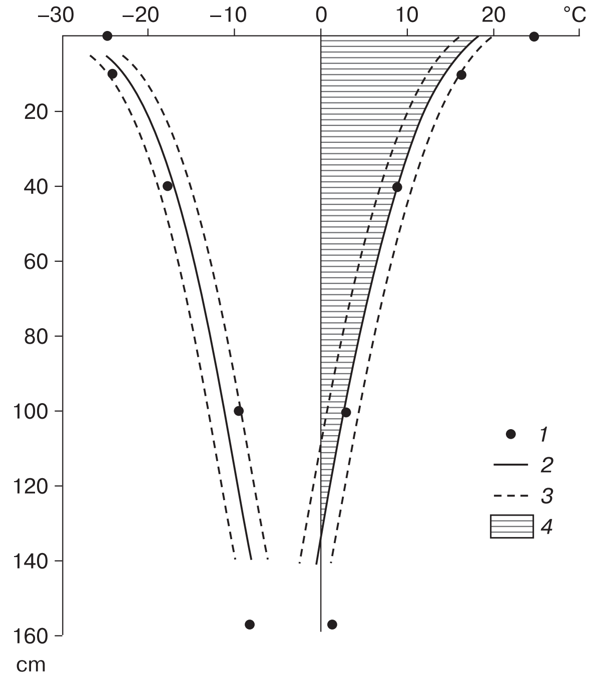

Fig. 1. Envelope curves of soil temperatures in the annual heat cycle.

1 – maximum and minimum mean daily soil temperatures; *2* – envelope curves; *3* – region of ⩾95 % confidence probability; *4* – region of $Q_{t>0}$.

SEASONAL AND LONG-TERM TEMPERATURE VARIATIONS

Seasonal variations in the temperatures of different soil types were plotted in contour lines using data averaged over the period of measurements (Fig. 2).

Seasonal thawing of soils begins in the latest May–mid-June at the extreme northern and western sites (R29A and R31, respectively) and after June 10 or occasionally in the earliest June, almost synchronously, within the Kolyma Lowland (Fig. 2), with two exceptions. Namely, thawing begins one or two weeks later in the taiga soil at site R36 near Andryushkino Community and at least two weeks earlier (latest April–earliest May) in the steppe patches of taiga in south-facing slopes (Fig. 2, *h*). The lag of thawing onset at the western sites (R29A, R31) behind that in the eastern sites is consistent with later transition to positive air temperatures recorded at the Tiksi and Chokurdakh weather stations relative to those at the Cherskiy station (Fig. 1 in [*Fedorov-Davydov et al., 1918*]); the air temperature transition at the Andryushkino weather station falls between the two.

Soils in Northern Yakutia thaw at different rates. Thaw depth reaches 10 cm in the latest June to mid-July in Arctic tundra gleysol (R29A), in June in typical and southern tundra loam soil, in latest May–earliest June in sandy soil, and after 15 May at most taiga sites. Hereafter soils are identified according to Field Identification Guide for Soils in Russia [*Khitrov, 2008*] and the WRB classification [*IUSS Working Group WRB, 2015*]. The time when thaw penetrates to a depth of 20 cm likewise varies as a function of soil type: within 20 July (Fig. 2, *a*), or even in earliest August in the coldest summer of 2009 in the soils of Arctic tundra and in middle–late June or earliest July in 2009 (Fig. 2, *b*) in typical tundra soils (turbic glacic cryosols); during June in southern tundra loam soil (loamic turbic glacic cryosols), and in earliest June (Fig. 2, *c*) at the southernmost site R22, with the same soil type; about a month later in organic gleysol (histic reductaquic cryosol) under troughs between hummocks where the mean June temperature remains negative. The tundra sandy podzolized brown soil called *podbur* in the Russian classification (spodic turbic cryosol) thaws to 20 cm slightly earlier than the loam soil: latest May–earliest June in the warm variety (R21, Fig. 2, *g*) and the first half of June in the cold variety (R16). Most of taiga soils thaw to this depth earlier or later in June: latest May–earliest June on south-facing slopes and latest June–earliest July (Fig. 2, *f*) in organic (folic) cryosol. The xeromorphic soil of taiga with steppe patches reaches the 20 cm thaw depth as early as before 20 May (Fig. 2, *h*), and this is the only soil type with positive May monthly mean temperatures.

Thaw depth never reaches 50 cm in the Artcic tundra (Fig. 2, *a*) but can penetrate as deep in typical tundra profiles at the Maliy Chukochy Cape, in July, in some years. Thaw reaches the 50 cm depth before 20 July in southern tundra (early August in the cold year 2009) and during July in the taiga cryometamorphic soil of R18 (Fig. 2, *d*). The warm variety of podbur soil (R21) thaws the fastest among zonal soils: till 50 cm before latest June (Fig. 2, *g*); its June monthly mean temperature is either positive or negative at this depth.

The period when temperatures fluctuate around zero during the thawing season lasts from 0 to

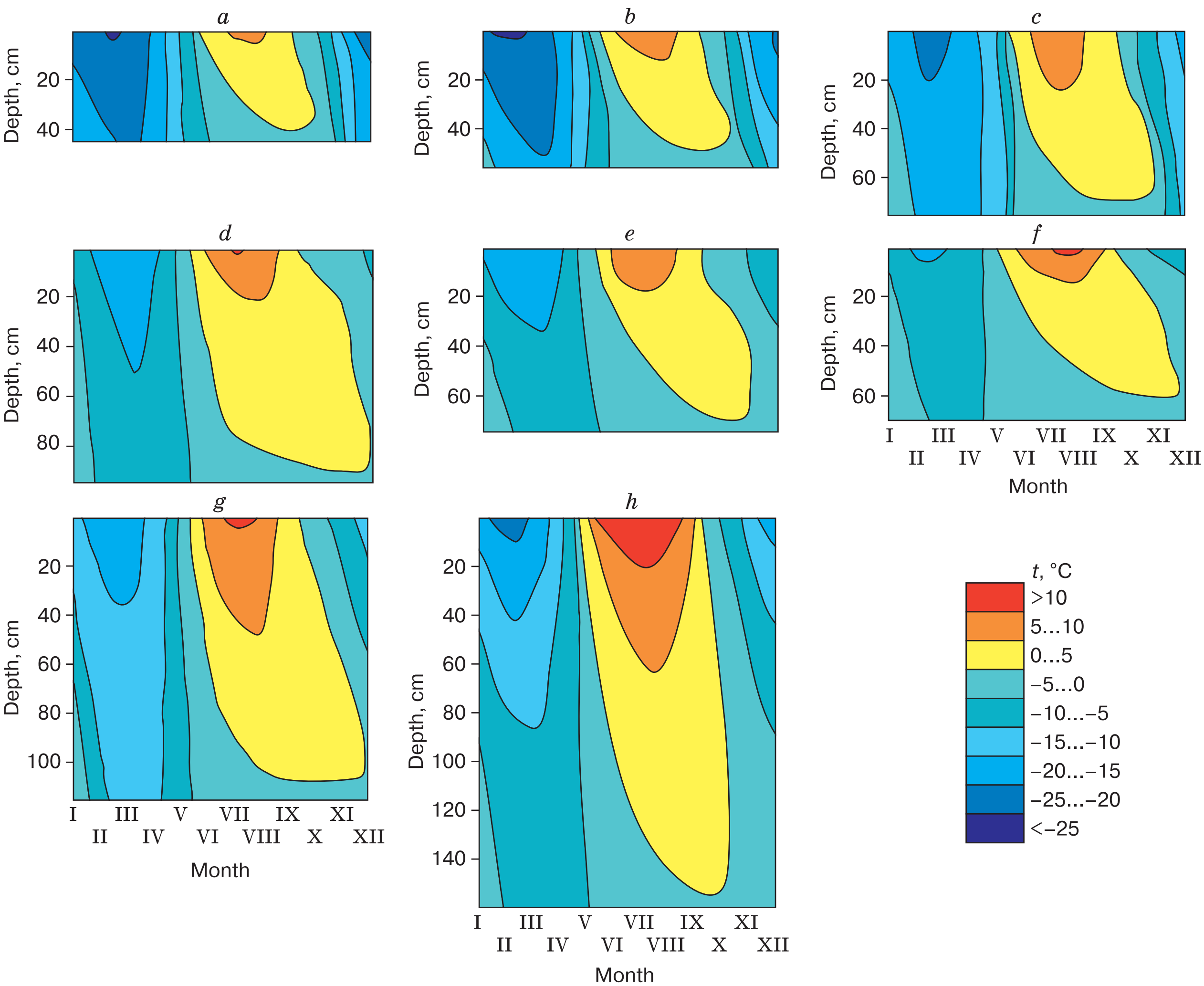

Fig. 2. Temperature patterns at different depths in soil profiles, based on data averaged over the observation period, for different sites.

a: Bykovsky Peninsula (ice complex), R29A; *b*: Cape Maliy Chukochy (ice complex), R13; *c*: Alazeya River, R22; *d*: Rodinka Hill (watershed), R18; *e*: Omolon River, R35; *f*: Rodinka Hill (slope-2), R18C; *g*: Lake Akhmelo, R21; *h*: Panteleikha River, Pan1.

10–12 days in tundra soils (20 and 50 cm thaw depths); 22 or even 35 days in peat-bearing (folic) cryosol at (R18C) in forest soil profiles, but no longer than 5 days in cryometamorphic soil on the south-facing slope at R18B. Soils at some sites (R13, R14, R35 and R18C) show short (a few days) freeze back spells at depths of 10–20 cm in early or middle June.

The >5 °C daily mean temperatures reach different depths depending on soil type and landscape zoning: 10 cm in Arctic tundra, 30–35 cm in typical and southern tundra (turbic glacic cryosols), and 30–40 cm in northern taiga. It reaches the 10 cm depth in July in the Bykovsky Peninsula (R29A) and already in June farther south. The >5 °C temperature at the 10 cm depth holds from 0–22 days in Arctic tundra, to 6–69 days in typical and southern tundra, and to 50–77 days in northern taiga.

The 5 °C isotherm never penetrates 20 cm deep in the Arctic tundra profile but reaches this depth in typical and southern tundra, commonly in July or less often in August. Soils in northern taiga (R18, R18B) and at its boundary (R22) keep this temperature in July and August every year, while the taiga cryometamorphic soil on south-facing slopes remains >5 °C warm at the 20 cm depth till September. In the abnormally warm year 2007, the 5 °C isotherm reached 20 cm after 10 or 20 June. The cryosol and gleysol profiles of boggy forest (R35, R36) reach this temperature in some years, but never at the folic cryosol site (R18C). The >5 °C temperatures at the 20 cm depth (Table 1) hold 0–36 days at tundra loam soil sites (R13, R14, and R31), 20–66 days at the southernmost site (R22), 19–59 days in the zonal soils of northern taiga (R18, R18B), and 0 to 44 days in boggy taiga (R35, R36).

The sandy podbur soil of the Khalelrchinskaya Tundra warms up to 5 °C as deep as 45 to 60 cm in different years. The temperature at the 20 cm depth exceeds 5 °C since June, almost every year, and holds in July and August, often till 10 September. The warm variety of this soil at R21 fails to reach >5 °C at the 50 cm depth only in 2013, while the cold variety (R16) reaches these temperatures once in three years, in the warm 2007. Sandy soils keep >5 °C warm for 53 to 93 days till 10 cm deep, 30–87 days to 20 cm, and 0–56 days to 50 cm (Table 1).

The soil of taiga with steppe patches at site Pan1 holds the ⩾5 °C temperature from May to September at the depths 10, 20 and 40 cm (Fig. 2, *h*) and till 70 cm from June to September.

Active mean daily temperatures of >10 °C reach 10 cm in July or August in some tundra (R13, R31) and taiga (R35) loamic soil profiles, in some years only, but occur more frequently and hold longer in taiga. The 10 °C isotherm closely approaches the 20 cm depth in some years but never penetrates deeper: the maximum daily means are 9.1–10.0 °C in southern tundra and 9.4–9.6 °C in northern taiga.

The >10 °C daily means in spodic turbic cryosols (podbur) reach depths of 25–30 cm and appear at 10 cm in June and at 20 cm in July and August. The warm variety of this soil at R21 warms up to >10 °C till 20 cm in seven out of nine years of observations, and the cold variety (R16) does only in one of three years. The >10 °C daily means persist as long as two months at 10 cm and no longer than three weeks (18–21 days) at 20 cm (Table 1).

The soil of taiga with steppe patches is warmer than 10 °C (daily means) at the depths 10 and 20 cm from July till August every year, and from May through September in two out of three years of observations. The >10 °C temperatures penetrate as deep as 40 and 70 cm (July–August) only in one year. The soil profile at CH-2 (Table 1) holds as warm as >10 °C for 72–98 days, >15 °C for 27–36 days, and >20 °C for 0–5 days till 20 cm. The temperatures exceed 10 °C till 70 cm down this profile for 16 days, but never rise above 15 °C at this depth.

The northern Yakutia soil profiles at 20 cm below the surface may reach highest temperatures in July or August. For instance, the watershed profile of site R18 in northern taiga becomes the warmest in August or as early as July on the south-facing slope. The temperature maximum penetrates till the 50 cm depth not before August. Soils begin cooling down in latest August in most cases.

The thaw depth reaches its maximum in September. The studied ecosystems have more than threefold difference in active layer thickness between small-scale landforms of different relative heights. Average thaw depths are 40–69 cm in tundra turbic glacic cryosols, 75–107 cm in tundra podbur soil, 90–100 cm in taiga cryometamorphic soil, 60–70 cm in taiga gleysol, cryosol, and organic cryosol, 45–54 cm in boggy soil, 65 cm in alluvial soil, and 154 cm in taiga with steppe patches (see Table 2 in [*Fedorov-Davydov et al., 2018*]). More details of seasonal thaw patterns were reported in our previous publications [*Fedorov-Davydov et al., 2004, 2008*].

Soils begin freezing in early September in the tundra of Arctic islands [*Doronina, 1963; Grigoriev, 1966*], in middle-late September in the mainland tundra, and in earliest October in the northern taiga subzone, the lag not exceeding three weeks. The season of freezing air temperatures begins about the same time (see Fig. 1 in [*Fedorov-Davydov et al., 2018*]).

The duration of the >0 °C soil temperature season depends mostly on the onset and rate of thawing. At the depth 20 cm, it lasts from 42–79 days in the Artcic tundra profiles to 145–153 days in taiga with steppe patches (Table 1). The difference is 2.3 times between soil types and 1.8 times (at 20 cm) or even 3.6 times (at 50 cm) between zonal soils (Table 1).

The soils of Northern Yakutia split into four groups according to average duration of the >0 °C season at a depth of 20 cm: (1) Arctic tundra gleysol,

Table 1. **Duration (days) of different temperature periods at the depths 20, 40 and 50 cm in soils of Northern Yakutia**

Site index	Temperature range, °C				
	>0	>5	>10	~0	<0
Depth 20 cm					
R29A	42–79	0	0	27–50	254–283
R13	71–105	0–36	0	20–40	230–270
R31	74–91	1–29	0	22–45	246–252
R14	82–106	0–35	0	19–41	238–264
R22	106–115	20–66	0	29–34	221–225
R16	101–104	30–69	0–18	8–27	234–253
R21	107–124	45–87	0–21	13–45	211–242
R18	99–117	19–31	0	48–73	176–207
R18B	109–123	43–59	0	83	159–173
R18C	83–88	0	0	50–111	171–227
R35	94–108	0–44	0	30–53	212–231
R36	86–93	0–27	0	43–49	220–230
CH-2	145–153	109–130	72–98	4–14	199–216
Depth 40 cm					
R18B	82–93	0	0	76–101	182–196
R18C	64–67	0	0	72–107	194–226
Pan1	130–139	70–90	0–2	7–41	194–219
Depth 50 cm					
R13	0–55	0	0	0–70	260–365
R14	43–59	0	0	31–54	253–291
R22	72–100	0	0	37–51	221–256
R22A	60	0	0	44	261
R16	76–102	0–12	0	41–49	222–240
R21	90–108	0–56	0	42–70	201–217
R18	80–96	0	0	53–90	180–226

64 days and (2) most tundra cryosols (turbic glacic cryosols) at R13, R14, R31, boggy taiga gleysol (reductaquic turbic cryosol) at R36 and organic (folic) cryosol at R18C, 84–92 days; (3) tundra cryosol (turbic glacic cryosol) near the taiga boundary (R22), tundra sandy podbur soil (spodic turbic cryosol) at R16, R21, non-boggy or slightly boggy taiga soils (cambic turbic and turbic glacic cryosols) at R18, R18B, and R35, 102–116 days; (4) soil in taiga with steppe patches (eutric loamic regsol) at CH-2, 150 days (Table 1). The respective average durations at the 50 cm depth (Table 1) are 27–51 days and 82–97 days for groups (2) and (3). Podbur profiles remain warm till 20 cm deep as long as four months. Note that *Savinov* [*1976*] who studied a more northern variety of the same sandy soil exposed to lower air temperatures reported duration within three months.

After the onset of fall freezing, the temperatures approach zero throughout the soil profiles. This happens 1–2 days after the soil surface temperatures become negative at most tundra loam soil sites and later in warmer soil varieties: 3–4 days in forest subzones, 4–5 days in podbur soils, 4–8 days in tundra cryosol near the northern boundary of taiga, and 3–10 days in taiga with steppe patches. The lags are the greatest in warmest years when soils store more heat during the summer season.

Active layer freezes up mostly from above. Partial freezing from below may occur at few sites in some years, more often in zonal tundra soils, as well as in intrazonal tundra varieties (e.g., alas-lagoon at R29D or boggy gully at R22A). The degree of freezing from below increases northward, which agrees with the ideas of *Sumgin et al.* [*1940*] and correlates with mean annual soil temperatures [*Pavlov, 1965, 1975*]. This degree is commonly greater in marine climate [*Pavlov, 1979; Romanovskiy, 1993*]: e.g., the Arctic tundra soil profile of Faddeevsky Island was reported to freeze from below over a half of its thickness [*Doronina, 1963*], and a similar freezing pattern was observed near Kazachy Community in mainland Yakutia [*Grigoriev, 1966*].

The tundra loam soil we studied froze upward from the active layer base in five out of nine years of our observations after cold summer seasons (1998, 1999, 2009, 2012, and 2013), and in some years earlier, according to published evidence [*Davydov and Butsenko, 1992*], while tundra sandy soils froze only from above. In some years, the active layer froze from below in the northern taiga subzone: it was recorded by temperature logging in the fall of 2005 on the south-facing slope at R18B and by Danilin frost-depth gauges in 1989. The duration of active layer freezing from below was 3–8 to 22–34 days in zonal tundra soils and reached a maximum of 67 days in boggy peat-bearing gleysol (R29D) and in cryometamorphic taiga soil on the south-facing slope (R18B). Most of profiles began freezing from above rather than from below, except for the soil of the Bykovsky Peninsula at R29D where freezing from below was recorded three weeks earlier in 2009.

The duration of the fall zero curtain varies in a large range depending on weather and pre-winter soil moisture content which increases systematically up the soil profile. This duration is on average 22–30 days for tundra loamic soils and 17–24 days in sandy podbur soil, at 20 cm depth; the respective values for the 50 cm depth are 38–60 days for loam and 46–50 days for podbur soils (Table 1). The soil temperature under the trough of site R22 fluctuates about zero for two weeks longer than that under the hummock at the same site. The period of near-zero soil temperatures at the 20 cm depth in taiga soil profiles lasts from 43 to 78 days in the vicinity of Cherskiy Community (R18, R18B, R18C) to 30–41 days at sites R35 and R36. The difference may be due to dryness and severity of winters increasing from east to west within the Kolyma Lowland (see Table 1 in [*Fedorov-Davydov et al., 2018*]). This period is as short as 6 days in xeromorphic soils of taiga with steppe patches at the 20 cm depth.

The lower part of the tundra soil profiles holds near-zero temperatures for 37–57 and 59–97 days in loam and sandy podbur soils, respectively, and for 49–94 days in the taiga variety of this soil. The forest soils in the vicinity of Cherskiy Community freeze up completely in 105–107 days (3.5 months). The perennial and seasonal freezing fronts in the taiga-steppe soil profiles meet in 37–63 days after near-zero temperatures have set up on the surface.

Freezing completes between mid-October and 10 November in tundra cryosols and after 10 or 20 November at the northern taiga boundary (R22). These estimates for tundra soils agree with earlier reports [*Tolstov, 1965; Grigoriev, 1966*]. In the cold and warm podbur profiles, the two freezing fronts meet between 10 November and mid-December and between mid-December and 10 January, respectively. The watershed cryometamorphic soil at R18 and organic cryosol (R18C) of the Cherskiy Community area freezes up about the same time as the warm podbur soil. Lower temperature gradients in taiga are balanced by a smaller thickness of the active layer. However, freezing completes later (in January and within 10 February) on the south-facing slope (R18B). The soil freezing pattern of taiga with steppe patches varies from year to year, and the process completes between 20 October and earliest December. Note for comparison that freezing of cryosols in the European northeast of Russia may complete as late as spring [*Mazhitova, 2008*].

The soil profile temperatures are the lowest in February or March at the depth 20 cm and in March at 50 cm. Winter daily mean temperatures fall below

–25 °C in most tundra soils of Northern Yakutia: to 10–15 cm depths every year and to 30–50 cm in some years at the Arctic and typical tundra sites; to 20–50 cm in some years in southern tundra cryosol; and to 10–20 cm in a few years at sites of sandy podbur soil. Daily means fall below –20 °C every year in the Artcic and typical tundra loam soil profiles; in some years in southern tundra; till a depth of 60 cm every year and 80 cm in some years in the cold variety of podbur soil, and to 50 cm in some years in the warm variety.

The taiga zone soils likewise show different winter temperature patterns. The forest cryosol (R35) and gleysol (R36) profiles are below –15 °C to 10–20 cm in some years and colder than –10 °C every year throughout the profile. The temperature of watershed cryometamorphic soil of Cherskiy vicinities decreases below –10 °C in some years throughout the profile but is never as cold on the south-facing slope (R18B, R18C). In the dry soil of taiga with steppe patches, the –20 °C isotherm reaches at least 20 cm and the –15 °C isotherm penetrates as deep as 40–70 cm.

The spring temperature inversion occurs commonly after 10 April or in early May.

The tundra soils commonly remain frozen longer than the taiga soils. This period lasts on average 265 days in Arctic tundra (R29A), 247–250 days in most tundra cryosols, 223 days at the northern taiga boundary (R22), 222–230 days in sandy podbur soil, 221–224 days in boggy taiga soil (R35, R36), and 167–199 days in the taiga soils near Cherskiy Community, at the 20 cm depth (Table 1). The season of frozen permafrost-affected soils has been commonly assumed to become longer down the profile [*Makeev et al., 1974*], but that is not always the case at the sites we monitored. Dry podbur and taiga-steppe soils at the 20 cm depth remain frozen longer than at 40–50 cm, as the upper profile part freezes up earlier (Table 1). The taiga soils of the south-facing slope at R18B and R18C stay frozen the longest in the middle part of the profile, because of later convergence of the seasonal and perennial freezing fronts.

It is also pertinent to discuss long-term variations in temperature parameters. Annual thawing degree-day sums vary from year to year and hardly can reveal any distinct trends: The period of our observations spans years with unusually warm (2007) and cold (2009) summers. In this respect, the freezing degree-day sums are more informative (Fig. 3) and show a soil warming trend since the latest 1990s. This trend follows the respective trend in air temperatures and agrees with the general change of the Eurasian climate through the recent decades. However, it remains unclear whether this warming is global and which climate cycle does it represent. Unfortunately, our dataset, with only nine years of observations, is incomplete and relatively small. Therefore, the active layer thickness is still a more reliable indicator of variations in the thermal state of soils.

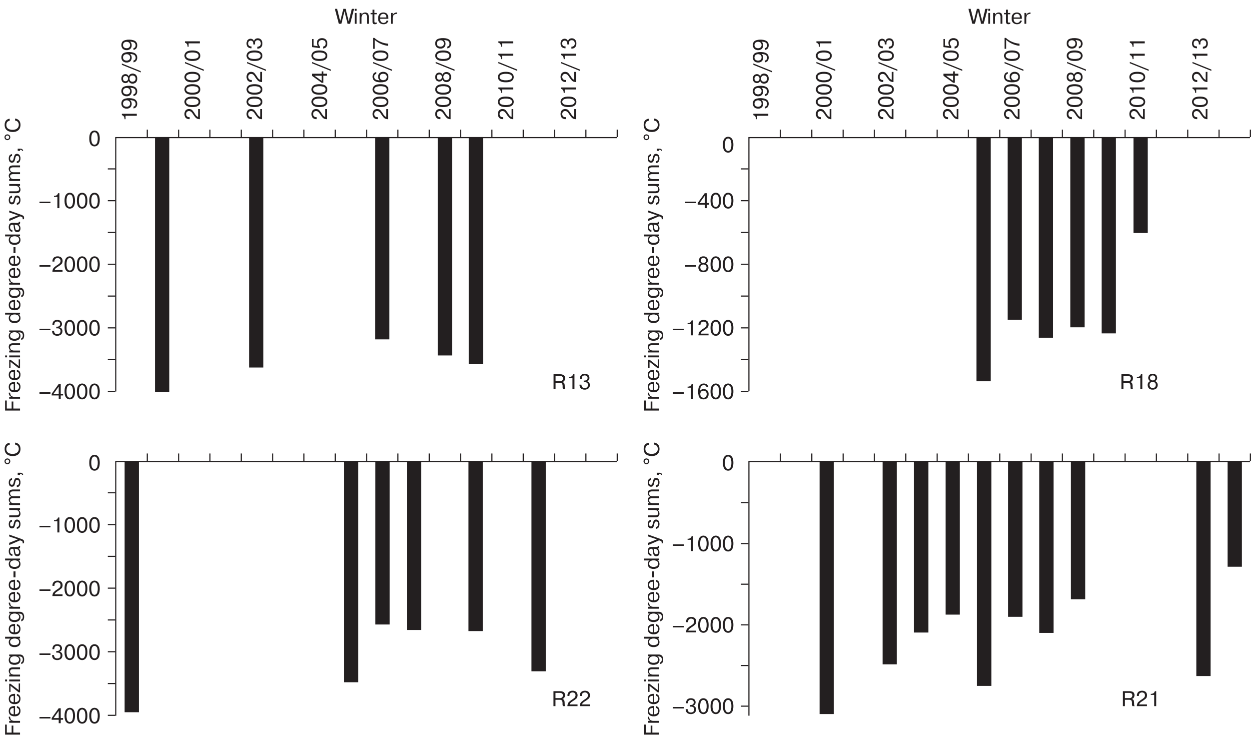

Fig. 3. Annual variations in freezing degree-day sums in different soil types, at a depth of 20 cm.

Table 2. **Warming heat, kcal/(m²·yr), at different soil sites in Northern Yakutia**

Year	R29A	R13	R31	R22	R18	R18B	R35	R18C	Amb	R16	R21	Pan1	CH-2
1999	–	–	–	2395	–	–	–	–	–	–	–	–	–
2000	–	1993	–	–	–	–	–	–	–	–	–	–	–
2004	–	–	–	–	–	–	–	–	–	–	5404	–	–
2005	–	–	–	–	–	4813	–	–	–	–	6039	–	–
2006	–	–	–	3363	3592	4439	–	1553	–	2765	4531	8123	–
2007	–	3159	–	4418	4714	–	–	2420	–	–	7030	11001	–
2008	–	3374	–	4390	–	–	–	–	–	–	5514	8617	12940
2009	863	2040	2600	3312	–	–	1945	1552	2115	3321	3584	–	–
2010	1642	3669	3659	4455	3482	–	2259	–	3194	4520	–	–	14560
2011	1565	–	3409	3247	–	–	2767	–	–	–	–	–	12823
2012	–	–	–	2762	–	–	3267	–	–	–	–	–	–
2013	–	–	2359	–	–	–	3852	–	–	–	4187	–	–
2014	–	–	2885	–	–	–	–	–	–	–	5044	–	–
Average	1357	2847	2981	3543	3929	4626	2818	1842	2654	3535	5167	9247	13441

HEAT PARAMETER $Q_{t>0}$

The reported temperature monitoring data have implications for the amount of heat spent on soil warming ($Q_{t>0}$) and its variations in ecological-genetic series. The heat parameter $Q_{t>0}$ varies largely from year to year in each soil profile (Table 2): the lowest in the cold summer of 2009 and the highest in the warm summers of 2007 and 2010. The difference between the lowest $Q_{t>0}$ in Arctic tundra gleysol (R29A) and the highest value in stony soil upon bedrock in taiga with steppe patches (CH-2) exceeds ten times.

The $Q_{t>0}$ distribution over the tundra soils follows the pattern of zones and subzones: it grows from 1360 to 3540 kcal/(m²·yr) from the Arctic tundra to the northern taiga boundary. This range encompasses the annual amount of heat spent for warming taiga cryosol (R35), organic cryosol (R18C), and alluvial silty-organic-gleyic soil (Amb). The average $Q_{t>0}$ value in the cold variety of sandy podbur soil is almost the same as in the southern variety of loamic cryosol. It is higher in taiga cryometamorphic soil 3930–4630 kcal/(m²·yr), which is slightly lower than in the warm variety of podbur soil, and the highest (9250–13440 kcal/(m²·yr)) in xeromorphic soils of taiga with steppe patches. Although being tentative, the obtained $Q_{t>0}$ series demonstrates that the formation of genetically different soils strongly depends on the amount of heat they receive.

CONCLUSIONS

1. Soil profiles in Northern Yakutia differ in average duration of the season of positive temperatures, the difference being 2.3 times between soil types and 1.8 between zonal loam soils, at a depth of 20 cm. The difference at a depth of 50 cm is still greater.

2. The seasons of >0 °C and >5 °C soil temperatures may be shorter in wetter boggy areas with thicker organic (peat) horizons, which shows up in both the tundra complex and at the soil mesostructure level.

3. In the fall, the active layer freezes mostly from above, except for the years of cool summer seasons in the tundra zone when it freezes partly from below, and the freezing begins later than the soil surface temperatures become stable negative. The frequency of this effect increases northward over the region. Sand soils never freeze from below.

4. The durations of fall freezing and persistent near-zero temperatures vary from 1–2 months for tundra cryosol and gleysol soils to 2.5–3.5 months for taiga cryometamorphic soil, organic cryosol, and tundra podbur soils. The zero curtain period is longer in taiga than in tundra and in loam soil than in sand, at the same depths below the surface.

5. The tundra and taiga soils show a warming trend of the soil climate since the late 1990s dynamics according to annual freezing degree-day sums.

6. The soils of Northern Yakutia vary in total heat spent on active layer thawing $Q_{t>0}$, the difference reaching 10 times. and make up the series: tundra loam soil; taiga gleysol, cryosol and organic cryosol; alluvial soils; tundra podbur and taiga cryometamorphic soils; soil of taiga with steppe patches.

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