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Recent air temperature changes in the permafrost landscapes of northeastern Eurasia

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Abstract

In the last two decades, climatic change has resulted in increased cryogenic activity in northeastern Eurasia, with adverse consequences for landscapes and socio-economic systems in the permafrost zone.

The main purpose of this study was to assess the recent phases of warming, starting with Arctic warming. We performed a spatiotemporal analysis of climatic conditions during phases of maximum warming (i.e., 1935–1945, 1988–1995, and 2005–2009) in northeastern Eurasia and compared the magnitude of warming and its effect on permafrost among these critical periods. Our observations of permafrost landscape dynamics confirmed that the last two warming phases have played major roles in changing the environment.

Data analysis has revealed regional patterns in the intensity of warming. Areas south of 60–62° latitude experienced no rise in air temperature during the Arctic warming period (1935–1945), whereas during 1988–1995, the center of warming shifted to the south of northeastern Eurasia. The last phase of warming (2005–2009) was characterized by maximum values of mean annual air temperature and the thawing index, and a decrease in the freezing index throughout northeastern Eurasia.

Keywords: Climate change; Freezing index; Thawing index; Permafrost landscape

1. Introduction

A significant modification of permafrost landscapes has been occurring in recent decades. A disturbance of the natural equilibrium associated with current warming and anthropogenic activity has resulted in the development of cryogenic processes. The increased rates of cryogenic activity have led to destabilization of the landscape and of life as a whole in the far north. The direct adverse consequences for human society include less usable land and damage to buildings and utilities.

Climate warming in the second half of the twentieth century has resulted in a nearly ubiquitous increase in ground temperature throughout the Russian permafrost region (e.g., Anisimov, 1989; Gilichinsky et al., 2000;

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Pavlov, 2001, 2008; Vasiliev, 1999; Varlamov et al., 2002; Izrael et al., 2002, 2006; Pavlov and Malkova, 2005, 2009; Iijima et al., 2010; Romanovsky et al., 2010). A similar trend is observed in other parts of the world, including North America (e.g., Osterkamp, 2005; Osterkamp and Romanovsky, 1999; Smith et al., 2010) Europe (e.g., Harris et al., 2003, 2009), and Asia (e.g., Jin et al., 2000, 2007; Marchenko et al., 2007; Zhao et al., 2010; Cheng and Jin, 2013).

Northeastern Eurasia is a vast area characterized by a great variety of landscapes ranging from Arctic tundra to steppes and from coastal lowlands to glaciered high mountains. This predetermines the diversity of landscape dynamics. Climate change is the main factor influencing the dynamics of modern landscapes. Therefore, spatial patterns in the distribution of current climatic changes in northeastern Eurasia have been studied.

Pavlov and Malkova (2005) identified four zones in northeastern Russia with respect to increases in the magnitude of mean annual air temperature (MAAT) during 1965–1995 relative to the mean values during 1951–1980: 1) very weak (departure from normal <0.3 °C/10 yr) in Arctic landscapes; 2) weak (0.3–0.7 °C/10 yr) in Arctic and Subarctic landscapes; 3) moderate (0.7–1 °C/10 yr) in the buffer zone between the Arctic tundra and taiga landscapes; and 4) strong (>1 °C/10 yr) in taiga landscapes. Such a division highlights the differentiation of climatic changes in different landscapes.

The same authors (Pavlov and Malkova, 2009) produced a map of northern Russia showing the linear trends in mean annual ground temperature over the period 1965 to 2005. The map divides northeastern Eurasia into three regions with different trends in increasing MAAT: <0.03 °C/yr, 0.03–0.05 °C/yr, and >0.05 °C/yr. The Arctic and Subarctic parts of Yakutia are clearly distinguishable on this map as having the lowest MAAT trends, while central Yakutia has the highest trends.

Skachkov (2005) analyzed the spatial variation in MAAT trends in Yakutia over the period 1965–1995. His map shows that the northwestern and far northeastern parts of Yakutia experienced the least warming, whereas the Lensk–Yakutsk area had the greatest increase in mean annual temperature.

Varlamov et al. (1998) performed a spatial analysis of current temperature changes in east Siberia and the Russian Far East. Against the background of marked interannual variation in MAAT, a significant linear trend (0.02–0.04 °C/yr) was observed in most parts of the southern and southwestern Far East. In his sketch map, northeastern Eurasia also displays variations in MAAT trends. The greatest variation in the trends occurred in winter and spring.

Fedorov and Svinoboev (2000) studied the regionalization of climate change in Yakutia in the second half of the twentieth century. They produced a map showing trends for the period from 1951 to 1989 that identified five regions. The greatest positive trend in mean annual air temperature (0.03–0.04 °C/yr) was observed in central Yakutia, while in the Oymyakon–Verkhoyansk region, no trend was noted in the tundra and tundra-forest belt, but negative trends were evident in the Anabar tundra, New Siberian Islands, and Kolyma–Indigirka tundra. In total, about 75% of Yakutia was located in the zone with positive MAAT trends.

The main purpose of this study was to determine regional patterns of recent climate fluctuations. After analyzing long-term air temperature variability in northeastern Eurasia, we selected three periods of warming: 1935–1945, 1988–1995, and 2005–2009. For comparison, data for the representative cooling period between 1961 and 1970 were also considered. The three periods of warming were assessed to determine in which landscapes each warming phase had the largest impact on permafrost.

Climate variations were analyzed based on departures of MAAT, the freezing index, and the thawing index.

2. Data sources and methods

To study climatic departures, we used the existing USSR physiographic classifications for landscape differentiation (e.g., Gvozdetskiy, 1968; Mil'kov, 1977; Isachenko, 1985). On these schematic maps, zonal and sectoral differences in the landscapes are clearly evident. For example, Gvozdetskiy (1968) subdivided the tundra zone into the Yenisey–Khatanga and Anabar–Olenek regions adjoining the Yenisey and Lena basins, respectively. Similar differences were found in the tundra-forest and northern open woodland zones (Yenisey–Olenek and Kotuy–Olenek), and in the taiga zone (Trans–Yenisey, Tunguska, Upper Vilyuy and Central Yakutian in the north and Angara and Cis–Sayan–Angara–Lena in the south). Landscape zones (tundra, tundra-forest, and northern, middle, and mountain taiga) were used as the basic units. Provincial differences in the landscape zones were taken into account (Fig. 1), with the Middle Siberia Province subdivided into the Yenisey and Lena sectors due to significant differences in permafrost conditions. Northeastern Siberia and the Far East sector also reflected

Fig. 1. Landscape zonation of northeastern Asia. Tundra: 1: Enisey sector of Middle Siberia; 2: Lena sector of Middle Siberia; 3: northeastern Siberia; 4: Far East sector Tundra-forest and Northern Taiga: 5: Enisey sector of Middle Siberia; 6: Lena sector of Middle Siberia; 7: northeastern Siberia; 8: Far East sector; Middle Taiga: 9: Lena sector of Middle Siberia (Central Yakutia); 10: Enisey sector of Middle Siberia; 11: Lena sector of Middle Siberia (southern part); Mountain Taiga: 12: south Siberian mountains, 13: Far East sector. The numerals 1–49 in blue circles represent the meteorological station (see Table 1).

the provincial peculiarities of the landscape zones. Data analysis and the determination of climatic departures were undertaken according to the matrix given in Table 1. Mean values of annual air temperature and the thawing and freezing indices from meteorological stations are given in Table 2.

The air temperature data were obtained from the NOAA database (www.ncdc.noaa.gov/ghcnm). For geographical locations where additional data were needed (Saskylakh, Tiksi, Ambarchik, Igarka, Volochanka, Kyusyur, Srednekolymsk, Susuman, Srednekan, and Verkhneimbatsk), the RIHMI-WDC database, Russia (www.meteo.ru/climate/sp_clim.php) was accessed. A total of 49 meteorological stations active since the 1930s were selected. For some landscape-climatic regions, such as the tundra-forest and northern taiga of the Lena region of Middle Siberia, we used only two meteorological stations (Zhigansk and Kyusyur) because others, such as Sukhana, Maak, Siktyakh, and Dzhardzhan only had records from 1951 onward, and the Olenek station was relocated, which affected the temperature time series. For these practical reasons, we were not able to provide a uniform data coverage for each region.

Departures in the MAAT and freezing and thawing indices were calculated relative to the long-term means for the period between 1930 and 2010 at each station. The selection of meteorological stations in the different landscape regions was made based on correlations in the data, with non-correlated data omitted.

Ground temperature analysis was possible where daily and mean monthly data at various depths were made available on the RIHMI-WDC website (www.meteo.ru/climate/sp_clim.php). For the tundra, tundra-forest, and the northern and mountain taiga landscapes, temperatures at 1.6-m depth were used in the analysis because the main stations record temperatures only to this depth. In these regions, permafrost is stable at 1.6 m in typical, undisturbed conditions, and the active layer is commonly located higher in the profile. For the middle taiga landscapes, we used temperatures at 3.2-m depth because the ground at this depth is nearly always frozen in the continuous permafrost zone, whereas in the discontinuous and sporadic permafrost zone, the freezing of thawed ground occurs mainly at this depth. The long-term mean was calculated from data for the period between 1977 and 2008, and all analyses were made relative to this period.

Time intervals were selected based on an analysis of long-term variations in mean annual air temperature and freezing index over the period 1930–2010 (Figs. 2–3). Arctic warming in northeastern Eurasia occurred from the mid-1930s to the mid-1940s (1935–1945), which can be clearly seen on the plot of freezing index variation

Table 1
Location of meteorological stations in reference to landscape and climatic regions.

Landscape zone	Provincial structure			
	Middle Siberia		North-east Siberia	Far east
	Yenisey sector	Lena sector		
Tundra	1. Dikson (73.50; 80.40; 47)[a] 2. Fedorov HMO (77.72; 104.30; 15) 3. Saskylakh (71.58; 114.05; 16)	4. Tiksi (71.35; 128.55; 8)[b] 5. Kotel'nyy (76.00; 137.87; 8) 6. Ambarchik (69.37; 162.18; 24)		7. Wrangell Island (70.98; −178.48; 5) 8. Cape Schmidt (68.90; −179.37; 4) 9. Uelen (66.17; −169.83; 3) 10. Anadyr' (64.78; 177.57; 61)
Tundra-Forest and Northern Taiga	11. Dudinka (69.40; 86.17; 19) 12. Igarka (67.28; 86.34; 20) 13. Volochanka (70.58; 94.30; 37) 14. Khatanga (71.98; 102.47; 33) 15. Turukhansk (65.78; 87.93; 38) 16. Verkhneimbatsk (63.09; 87.57; 46) 17. Tura (64.27; 100.23; 168)	18. Zhigansk (66.77; 123.40; 92) 19. Kyusyur (70.41; 127.24; 30)	20. Verkhoyansk (67.55; 133.38; 137) 21. Oymyakon (63.25; 143.15; 741) 22. Zyryanka (65.73; 150.90; 43) 23. Srednekolymsk (67.27; 153.43; 20)	24. Susuman (62.47; 148.10; 645) 25. Srednekan (62.27; 152.19; 264) 26. Seymchan (62.92; 152.42; 205)
Middle Taiga	27. Bor (61.60; 90.02; 58) 28. Baykit (61.67; 96.37; 262) 29. Vanavara (60.33; 102.27; 260) 30. Kirensk (57.77; 108.07; 259)	31. Vilyuysk (63.77; 121.62; 111) 32. Isit' (60.82; 125.32; 118) 33. Yakutsk (62.02; 129.72; 101) 34. Ust'-Maya (60.38; 134.45; 170) 35. Vitim (59.45; 112.58; 190) 36. Olekminsk (60.40; 120.42; 226) 37. Aldan (58.62; 125.37; 682)	–	–
Mountain Taiga	38. Nizhneangarsk (55.47; 109.33; 487) 39. Ust'-Barguzin (53.42; 109.02; 461) 40. Barguzin (53.62; 109.63; 489) 41. Bagdarin (54.47; 113.58; 903) 42. Kalakan (55.12; 116.77; 613) 43. Mogocha (53.75; 119.73; 625)		44. Bomnak (54.72; 128.93; 357) 45. Norsk (52.35; 129.92; 208) 46. Ekimchan (53.07; 132.98; 542) 47. Polina Osipenko (52.42; 136.50; 73) 48. Ayan (56.45; 138.15; 8) 49. Okhotsk (59.37; 143.20; 6)	

[a] Bracketed numbers are latitude, longitude, ASL (m) in course.
[b] Number of meteorological station in Fig. 1.

(see Fig. 3). This period is also clearly distinguishable against the cooling period between 1950 and 1970 (see Fig. 2) on the plot of MAAT variation. The next warming phase began at the end of the 1980s and continued to the mid-1990s. Following our analysis of the air temperature variations in all regions, we used the time interval between 1988 and 1995 to assess the second phase of warming. A ubiquitous increase in air temperature began in 2005, reaching its peak in the period 2005–2009, and this interval was used as the third period of warming in northeastern Eurasia.

3. Results

3.1. Mean annual air temperature

As noted above, different regions in northeastern Eurasia respond differently to changes in climate. We investigated changes in MAAT in the study region using representative meteorological stations in the landscape regions (Table 3).

The results given in Table 2 confirm that climate change is not uniform throughout northeastern Eurasia.

Table 2
Mean statistic characteristics MAAT, FI and TI on meteorological stations.

No[a]	Station	MAAT					TI					FI				
		Average annual, °C	Std	Var	Trend, °C/yr	R^2	Average annual, °C*day	Std	Var	Trend, °C-day/yr	R^2	Average annual, °C*day	Std	Var	Trend, °C-day/yr	R^2
1	Dikson	−11.2	1.4	12.1	0.00	0.01	370	124.9	33.8	0.15	0.00	−4508	481.9	10.7	−2.69	0.02
2	Fedorov HMO	−14.6	1.3	9.2	0.00	0.00	70	36.4	51.9	−0.01	0.00	−5439	477.9	8.8	−1.13	0.00
3	Saskylakh	−14.1	1.4	9.7	−0.01	0.02	817	121.7	14.9	−0.43	0.00	−6010	450.7	7.5	−3.73	0.03
4	Tiksi	−13.1	1.3	10.0	0.00	0.00	599	129.0	21.5	0.00	0.00	−5394	419.5	7.8	0.88	0.00
5	Kotel'nyy	−14.6	1.2	8.3	0.01	0.02	156	90.0	57.8	0.63	0.02	−5519	353.2	6.4	0.79	0.00
6	Ambarchik	−12.4	1.1	9.0	0.01	0.05	551	156.4	28.4	1.69	0.06	−5090	349.3	6.9	2.29	0.02
7	Wrangell Island	−11.0	1.2	10.9	0.02	0.23	185	103.6	55.9	1.93	0.19	−4230	362.8	8.6	6.99	0.21
8	Cape Schmidt	−11.5	1.2	10.8	0.03	0.22	310	127.1	41.0	2.60	0.22	−4543	388.1	8.5	6.33	0.14
9	Uelen	−7.4	1.3	17.4	0.02	0.11	536	117.2	21.8	2.59	0.27	−3264	377.3	11.6	3.94	0.06
10	Anadyr'	−7.3	1.1	14.7	0.01	0.05	946	121.2	12.8	2.43	0.22	−3619	351.7	9.7	1.28	0.01
11	Dudinka	−9.8	1.4	14.5	0.00	0.00	1038	152.0	14.6	1.63	0.06	−4625	503.0	10.9	−1.58	0.00
12	Igarka	−8.1	1.4	16.8	0.01	0.01	1265	139.7	11.0	1.29	0.05	−4241	470.9	11.1	1.05	0.00
13	Volochanka	−11.6	1.4	12.2	0.00	0.00	950	146.5	15.4	0.47	0.01	−5229	534.5	10.2	0.39	0.00
14	Khatanga	−12.8	1.3	10.4	0.01	0.01	895	133.1	14.9	0.53	0.01	−5608	467.0	8.3	1.16	0.01
15	Turukhansk	−6.3	1.3	20.6	0.00	0.01	1433	145.0	10.1	1.00	0.03	−3758	446.0	11.9	0.74	0.00
16	Verkhneimbatsk	−4.5	1.3	29.2	0.01	0.05	1628	138.0	8.5	2.15	0.13	−3282	424.7	12.9	2.98	0.03
17	Tura	−9.0	1.3	14.8	0.01	0.05	1532	128.8	8.4	1.12	0.04	−4839	449.8	9.3	3.38	0.03
18	Zhigansk	−11.5	1.1	9.4	0.01	0.05	1398	135.5	9.7	0.60	0.01	−5623	323.0	5.7	3.43	0.05
19	Kyusyur	−13.4	1.2	8.6	0.00	0.01	982	133.5	13.6	−0.10	0.00	−5909	374.6	6.3	−0.93	0.00
20	Verkhoyansk	−15.0	1.2	7.8	0.02	0.10	1391	158.9	11.4	1.77	0.07	−6923	360.2	5.2	4.16	0.07
21	Oymyakon	−16.1	1.0	6.4	0.02	0.18	1253	138.7	11.1	1.79	0.09	−7181	319.8	4.5	5.05	0.13
22	Zyryanka	−11.1	1.0	8.8	0.02	0.17	1472	155.9	10.6	2.35	0.11	−5535	251.8	4.5	3.90	0.11
23	Srednekolymsk	−11.9	1.1	9.2	0.02	0.12	1236	154.9	12.5	2.16	0.11	−5629	282.6	5.0	3.83	0.10
24	Susuman	−12.7	1.1	8.9	0.03	0.33	1226	132.6	10.8	3.33	0.28	−5889	350.3	5.9	7.53	0.20
25	Srednekan	−10.9	1.1	10.3	0.03	0.31	1492	160.8	10.8	3.08	0.17	−5502	316.7	5.8	7.25	0.26
26	Seymchan	−11.1	1.1	9.7	0.02	0.17	1527	139.1	9.1	1.91	0.09	−5592	289.6	5.2	4.79	0.13
27	Bor	−3.7	1.3	35.7	0.01	0.06	1773	115.5	6.5	1.40	0.07	−3118	427.8	13.7	3.91	0.04
28	Baykit	−6.4	1.4	21.3	0.02	0.07	1609	107.1	6.7	1.09	0.05	−3964	447.6	11.3	4.94	0.06
29	Vanavara	−5.7	1.3	23.3	0.01	0.06	1710	117.5	6.9	1.89	0.14	−3819	448.4	11.7	2.82	0.02
30	Kirensk	−4.0	1.3	31.3	0.01	0.02	1908	117.4	6.2	0.90	0.03	−3376	427.6	12.7	2.20	0.01
31	Vilyuysk	−8.9	1.3	14.1	0.01	0.08	1781	132.5	7.4	1.22	0.05	−5040	407.6	8.1	4.33	0.06
32	Isit'	−7.8	1.2	15.1	0.01	0.02	1828	119.6	6.5	−0.07	0.00	−4707	382.8	8.1	2.93	0.03
33	Yakutsk	−9.7	1.2	12.8	0.03	0.26	1928	125.3	6.5	1.18	0.05	−5485	392.4	7.2	8.68	0.27
34	Ust'-Maya	−9.5	1.1	12.8	0.02	0.14	1866	123.6	6.6	1.56	0.09	−5375	346.2	6.4	4.84	0.11
35	Vitim	−5.2	1.3	25.4	0.02	0.08	1821	120.7	6.6	1.81	0.13	−3732	449.2	12.0	4.20	0.05
36	Olekminsk	−6.3	1.2	19.6	0.01	0.05	1864	127.5	6.8	−0.45	0.01	−4165	428.8	10.3	4.87	0.07
37	Aldan	−5.9	1.1	18.3	0.01	0.06	1621	130.7	8.1	0.35	0.00	−3800	344.4	9.1	4.08	0.07
38	Nizhneangarsk	−2.7	1.0	37.1	0.02	0.21	1709	144.5	8.5	3.41	0.29	−2680	300.5	11.2	3.73	0.08
39	Ust'-Barguzin	−2.1	1.0	46.6	0.03	0.40	1591	99.2	6.2	2.37	0.28	−2476	315.5	12.7	7.06	0.24

40	Barguzin	−2.6	1.0	39.8	0.02	0.18	2075	123.4	5.9	2.23	0.18	−3019	334.8	11.1	4.66	0.10
41	Bagdarin	−5.9	1.0	17.5	0.02	0.17	1591	99.2	6.2	2.37	0.28	−3744	366.7	9.8	4.90	0.08
42	Kalakan	−7.3	1.0	13.3	0.02	0.11	1718	91.7	5.3	0.50	0.01	−4383	326.3	7.4	5.47	0.13
43	Mogocha	−5.0	0.9	17.2	0.02	0.17	1806	95.0	5.3	1.45	0.13	−3642	300.0	8.2	4.10	0.10
44	Bomnak	−4.6	1.0	21.6	0.02	0.21	2011	116.4	5.8	1.73	0.12	−3724	317.5	8.5	5.09	0.14
45	Norsk	−3.3	1.1	32.8	0.02	0.17	2307	119.5	5.2	1.19	0.05	−3512	349.1	9.9	5.98	0.15
46	Ekimchan	−5.4	1.0	18.3	0.02	0.27	1845	117.1	6.3	1.56	0.10	−3822	282.8	7.4	6.17	0.26
47	Polina Osipenko	−2.6	1.0	39.2	0.02	0.27	2131	134.0	6.3	2.86	0.23	−3090	288.1	9.3	5.98	0.21
48	Ayan	−2.8	0.9	31.5	0.01	0.13	1351	134.1	9.9	1.98	0.11	−2367	251	10.6	2.91	0.07
49	Okhotsk	−4.3	0.9	19.9	0.02	0.23	1314	122.7	9.3	2.31	0.20	−2907	269.6	9.3	4.26	0.14

Abbreviations: MAAT – mean annual air temperature, TI – thawing index, FI – freezing index.
Std – standard deviation, Var – coefficient of variation, R^2 – coefficient of determination.

[a] Number of meteorological station in Fig. 1.

Whereas the tundra, tundra-forest, and northern taiga landscapes (except the Far East sector) experienced a significant increase in MAAT over the period 1935–1945, the middle taiga and mountain taiga areas experienced cooling. This latitudinal effect was characteristic in all landscape zones.

The variation in MAAT during the period 1935–1945 was also longitudinally dependent. In the tundra, tundra-forest, and northern taiga landscapes, which experienced the greatest warming effect during this period, departures in the MAAT varied in a west-to-east direction from positive (+0.8 + 1.1 °C in the Yenisey sector of Middle Siberia) to negative (−0.1 °C in the Far East sector).

The next phase of warming (1988–1995) had the greatest impact in the southern part of the study region, i.e., in the middle taiga of Middle Siberia and in the mountain taiga of southern Siberia. Interestingly, negative departures (−0.3 °C) were experienced in the tundra zone of the Yenisey sector in Middle Siberia. During this period the warming values did not reach the level of the Arctic warming of 1935–1945 in tundra landscapes, except in the Far East sector.

In the period between 2005 and 2009, the focus of the warming shifted northwards. The tundra, tundra-forest, and northern taiga landscapes experienced maximum warming that even exceeded the warming experienced between the 1930s and 1940s. A characteristic feature of this warming phase was that air temperatures were lower relative to the previous warming phase (1988–1995) in the discontinuous and sporadic permafrost zone (tundra-forest and northern and middle taigas in the Yenisey sector of Middle Siberia, middle taiga in the Lena sector of Middle Siberia, and mountain taiga in southern Siberia).

For comparison, Table 3 presents departures in the MAAT during the phase of cooling from 1961 to 1970. Air temperatures were maximally cold in all landscapes. The greatest negative departures in MAAT were experienced in tundra landscapes in the Yenisey sector of Middle Siberia.

3.2. Freezing index

Climate change has primarily been associated with changes in the winter temperature, which is expressed by the freezing index as an absolute value of the sum of negative mean daily air temperatures. As seen from the analysis, just as with the MAAT, different landscapes in northeastern Eurasia also respond differently to changes in climate (Table 4).

The results indicate that the changes in freezing conditions vary regionally. During the Arctic warming

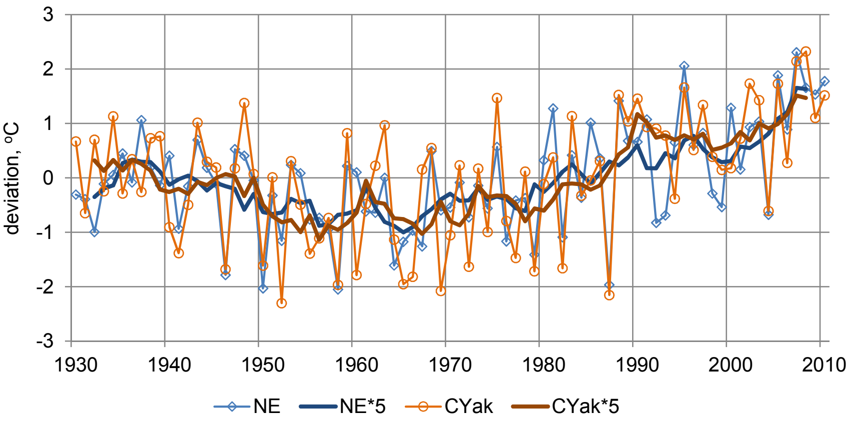

Fig. 2. Generalized model of the variation in mean annual temperature departure in the tundra of northeastern Siberia and in the taiga of central Yakutia.

period (1935–1945), the freezing index significantly decreased in the tundra, tundra-forest, and northern taiga landscapes except for the Far East sector, whereas in the areas of middle taiga in the Lena part of Middle Siberia and in the areas of mountain taiga in the southern Siberia mountains, the freezing index increased with cooling.

In tundra, tundra-forest, and northern taiga landscapes, the winter warming effect declined from west to east. The difference in freezing index values between the Yenisey and Far East sectors of tundra, tundra-forest, and northern taiga was about 315–320 °C*days. A similar effect was also observed in the mountain landscapes of south Siberia, where positive freezing index departures were recorded. In the Lena region, the departure was slightly less than that in the Far East region.

The warming phase between 1988 and 1995 had the greatest effect in southern areas. The maximum annual departures in the freezing index ranged between −350 and −360 °C*days in the middle taiga, which is underlain by discontinuous and sporadic permafrost, and were slightly less (about −270 °C*days) in the middle taiga of central Yakutia, which has continuous permafrost. Negative departures were experienced in the tundra (the Yenisey and Far East sectors). A slight decrease of up to 70 °C*days occurred in the Lena and northeastern sectors of the tundra. In tundra-forest and northern taiga landscapes, there was also a weakening of the warming in the west–east direction that ranged from −178 °C*days in the Yenisey sector through −105 °C*days in the Lena and northeastern sectors to −50 °C*days in the Far East sector. The Lena sector of mountain taiga (−292 °C*days) experienced greater warming than the Far East sector (−225 °C*days) did.

During the period between 2005 and 2009, tundra, tundra-forest, and northern taiga landscapes received, on average, 360–440 °C*days less cold due to the northward shift of the warming focus. This accounted for approximately 7–10% of the sum of negative temperatures in

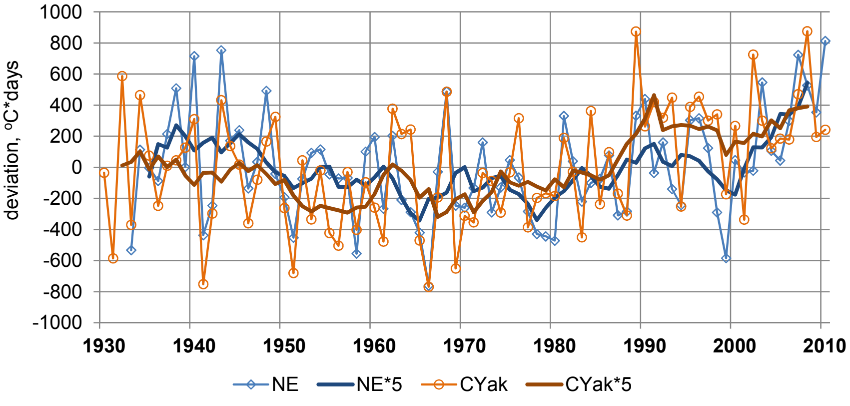

Fig. 3. Generalized model of the variation of freezing index departure in the tundra of northeastern Siberia and in the taiga of central Yakutia.

Table 3
Variation in MAAT departure in different periods in NE Eurasia, °C

Landscapes	Shift periods			
	1935–1945	1961–1970	1988–1995	2005–2009
Middle Siberia (Yenisey Basin)				
Tundra	1.1	−0.9	−0.3	1.5
Tundra-Forest	0.8	−0.7	0.4	1.2
Northern Taiga	0.4	−0.6	0.9	0.9
Middle Taiga	0.0	−0.7	1.3	0.70
Middle Siberia (Lena Basin)				
Tundra	0.6	−0.6	0.4	1.5
Northern Taiga	0.4	−0.5	0.5	1.1
Middle Taiga (Central Yakutia)	0.0	−0.7	1.0	1.5
Middle Taiga	−0.2	−0.5	1.3	0.7
Mountain Taiga	−0.3	−0.6	1.1	0.8
North East Siberia				
Tundra	0.6	−0.6	0.4	1.5
Northern Taiga	0.2	−0.7	0.7	1.8
Far East				
Tundra	0.0	−0.3	0.2	1.5
Northern Taiga	−0.1	−0.7	0.5	1.7
Mountain Taiga	−0.4	−0.5	0.9	1.1

these regions. Middle taiga landscapes in central Yakutia did not gain the same amount of cold during this period. In this period, the tundra, tundra-forest, and northern taiga landscapes of the northeastern and Far East sectors were warmer by 220–350 °C*days than they were during the earlier Arctic warming phase. In the Yenisey sector of the tundra, the freezing index was less than that in the Arctic warming phase.

Table 4
Variation in freezing index departures in different periods in NE Eurasia, °C*days.

Landscapes	Shift periods			
	1935–1945	1961–1970	1988–1995	2005–2009
Middle Siberia (Yenisey Basin)				
Tundra	−381	288	83	−441
Tundra-Forest	−272	188	−178	−375
Northern Taiga	−118	166	−269	−286
Middle Taiga	−7	171	−363	−253
Middle Siberia (Lena Basin)				
Tundra	−169	176	−70	−393
Northern Taiga	−74	135	−105	−242
Middle Taiga (Central Yakutia)	13	156	−268	−380
Middle Taiga	146	153	−347	−219
Mountain Taiga	61	155	−292	−211
North East Siberia				
Tundra	−169	176	−70	−393
Northern Taiga	−53	153	−104	−367
Far East				
Tundra	−65	57	19	−355
Northern Taiga	49	156	−50	−307
Mountain Taiga	91	110	−225	−265

Table 5
Variation in thawing index departures in different periods in NE Eurasia, °C*days.

Landscapes	Shift periods			
	1935–1945	1961–1970	1988–1995	2005–2009
Middle Siberia (Yenisey Basin)				
Tundra	47	−41	−26	75
Tundra-Forest	42	−67	−44	119
Northern Taiga	33	−62	8	131
Middle Taiga	20	−66	24	111
Middle Siberia (Lena Basin)				
Tundra	10	−38	39	132
Northern Taiga	55	−43	26	120
Middle Taiga (Central Yakutia)	24	−88	21	156
Middle Taiga	34	−67	33	123
Mountain Taiga	−35	−58	57	122
North East Siberia				
Tundra	10	−38	39	132
Northern Taiga	24	−64	80	213
Far East				
Tundra	−14	−44	39	177
Northern Taiga	−10	−37	71	243
Mountain Taiga	−37	−61	79	124

During the period of cooling (1961–1970), departures of the freezing index were maximally positive in all landscapes. The most pronounced spatial pattern was the meridional weakening of cooling from west to east in the tundra. Tundra landscapes in the Yenisey area gained much more cold (−288*days) than did those in the Lena (−176*days) and Far East (−57 °C*days) areas.

3.3. Thawing index

The thawing index, or the sum of positive mean daily air temperatures, is a measure of stored heat resources of permafrost landscapes and has profound significance for understanding their dynamics. The thawing index indicated that the landscapes in the studied regions developed differently during the study period (Table 5).

During the period of Arctic warming (1935–1945), the thawing index increased in all landscapes except the Far East sector and the mountains of southern Siberia. The general pattern of the decline in warming effect discussed in regard to the MAAT and freezing index was repeated from west to east in the tundra (from 47 to −14 °C*days) and from north to south in the Yenisey sector of Middle Siberia (from 47 to 20 °C*days). In the

Lena sector of Middle Siberia and northeastern Siberia, the greatest summer warming was observed in the tundra-forest and northern taiga during this period. It is interesting that in the Lena sector of Middle Siberia in the middle taiga landscapes of central, southwestern, and southern Yakutia, positive departures of summer temperatures were observed during this time, whereas annual and winter temperatures decreased. In the mountain landscapes of southern Siberia, the departures of the thawing index were negative.

The summer warming phase between 1988 and 1995 was focused in the tundra-forest and northern taiga of northeastern Siberia and the Far East sector and in the mountain landscapes of southern Siberia (about +60–80 °C*days). In tundra and tundra-forest landscapes of the Yenisey sector of Middle Siberia, the thawing index revealed negative departures (−26 to −44 °C*days). Elsewhere, the effect of summer warming was in the range of +20 to +40 °C*days.

The period between 2005 and 2009 was characterized by an overall increase in the thawing index in all regions. The greatest changes occurred in the tundra-forest and northern taiga of northeastern Siberia and the Far East (about +210–240 °C*days). Whereas the mean departures of the thawing index were 20–40*days during 1935–1945 and 1988–1995, during the warming period between 2005 and 2009, they reached an average of 100–130 °C*days.

For comparison, all landscapes experienced the maximum negative values of the thawing index during the general cooling period between 1961 and 1970. The departures were −88 °C*days in central Yakutia, −30 to −44 °C*days throughout the tundra zone, and −37 to −67 °C*days in the tundra-forest and northern taiga. Summers were quite cold in the middle taiga with discontinuous and sporadic permafrost in Middle Siberia and in the mountain taiga of southern Siberia.

4. Discussion

The development of abrupt climate change has had a profound influence on the state of permafrost (Iijima et al., 2010), resulting in significant ground warming, increased thawing depths, and an acceleration of cryogenic processes. However, no adequate comparison of the current state of the climate and the permafrost with previous phases of warming and cooling and no determination of the degree of hazard associated with the current situation have been undertaken. We therefore compared three phases of recent warming (1935–1945, 1988–1995, and 2005–2009) from both a climatic and geocryological perspective.

4.1. Tundra landscapes

Widespread warming in the period between 2005 and 2009 exceeded all of the parameters of the Arctic warming in the period between 1935 and 1945 in tundra landscapes. The MAAT during 2005–2009 was 1.5 °C above the long-term mean, whereas during 1935–1945, it was higher by 0.6–1.1 °C, except in the Far East sector, where no departures from the long-term mean were observed. The warming phase between 1988 and 1995 was generally no stronger than the Arctic warming (up to +0.4 °C). Temperatures of 0.3 °C below the long-term average were observed in the Yenisey sector of Middle Siberia during these years.

The freezing index during 2005–2009 was lower than that during 1935–1945. Index values ranged from 2 to 9% in the Far East sector and from 4 to 7% in the Lena and northeastern sectors; in the Yenisey sector, they were similar at 7–8%.

The value of the thawing index in the tundra of the Yenisey sector between 1935 and 1945 was 10% higher than the mean value between 1930 and 2010 and as much as 16% higher than that between 2005 and 2009. In the Lena and east Siberian sectors the increases were 5 and 30%, respectively, and the Far East sector experienced a 5% decrease and a 56% increase, respectively.

Morgenstern et al. (2011) studied thermokarst lakes in the Lena delta and confirmed that there was potential for active thermokarst development on yedomas with ice-rich deposits. The study reported 1813 such lakes ranging from 900 to 14,400 m^2 in size, which represented a mean area of about 3000 m^2, or 0.3 ha. This suggests that, as in central Yakutia, the thermokarst process is very active above the Arctic Circle. According to our calculations, thermokarst ponds in this size range on the Lena–Amga watershed have increased in size by a factor of 3–4 over a 30-year period, and water from melting ground ice may comprise about 30% of the input to the local water balance (Fedorov et al., 2013).

Grigoriev et al. (2006) reported that thermal erosion on ice-rich arctic coasts in east Siberia is activated with increasing air temperature, and this occurred during the 1930s and 1940s and the 1980s and 1990s. Later, Grigoriev (2008) observed a peak in thermal erosion activity in 2006–2008 that was associated with an abrupt increase in the air temperature in the eastern Siberian part of the Arctic.

Based on an interpretation of satellite images from 1974 to 2000, Walter et al. (2006) found not only an

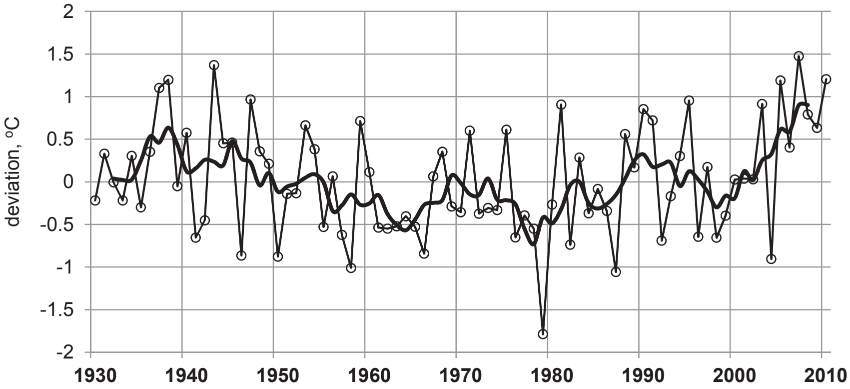

Fig. 4. Generalized model of the 1.6-m ground temperature departure in the tundra zone in the Lena and northeastern sectors.

expansion of existing thaw lakes in the Chersky area of the lower Kolyma River but also the appearance of new lakes. Using satellite images from 1977 to 2010, van Huissteden et al. (2012) identified a threefold increase in the number of thaw ponds in the Chokurdakh area of the lower Indigirka River, as well as a significant expansion in their area. This suggests that significant permafrost degradation is occurring.

Data from the Circumpolar Active Layer Monitoring (CALM) Program (http://www.gwu.edu/~calm/data/north.html) indicate that in the lower Kolyma tundra, thaw depths at measurement sites increased by an average of 17% between 2005 and 2010 compared with the period between 1996 and 2004, or by 10 cm, on average (ranging from 3 to 23 cm). The thaw depth in Chukotka increased during these years by 18–19% (8–9 cm).

Meteorological stations in the tundra zone do not measure ground temperatures. The data from meteorological stations nearest to the tundra zone indicate that ground temperatures also showed an abrupt increase in the 2000s. For example, mean annual ground temperatures (MAGTs) at 1.6-m depth were warmer between 2005 and 2008 than in the period between 1988 and 1995, by almost 1 °C in Igarka and Noril'sk and by 1.5 °C in Olenek and Verkhoyansk. According to data courteously provided by V. G. Rusakov, the MAGT at 3-m depth in Tiksi was 1.2 °C warmer between 2005 and 2008 compared with the period between 1996 and 2004.

Borehole measurements made by V. G. Rusakov during 1992–2009 in the vicinity of Tiksi revealed that ground temperatures were well correlated with mean monthly air temperatures, with a time lag of two months at depths of 1, 2, and 3 m (correlation coefficients of 0.91–0.97 at the 95% significance level). Based on this empirically identified dependence, we determined the variation in ground temperature at 1.6-m depth for the tundra zone from MAATs at the Saskylakh, Tiksi, Chokurdakh, Kotel'nyy, and Shalaurov meteorological stations for the period between 1930 and 2010. According to Fig. 4, which shows departure of ground temperatures at 1.6-m depth, the warming between 1935 and 1945 was greater than between 1988 and 1995; however, the magnitude of warming in the 2000s exceeds both of these periods.

Thus, the geocryological situation in the tundra zone of northeastern Eurasia has been aggravated in the 2000s compared comparison with the period between 1988 and 1995. The climatic characteristics also indicate that the geocryological risk for landscapes was not as strong in the period between 1935 and 1945 as it has been in subsequent years.

4.2. Tundra-forest and northern taiga landscapes

Tundra-forest and northern taiga landscapes occupy vast areas, encompassing the northern part of the Siberian plateau, the Yana and El'ga plateaus, the Kolyma–Indigirka lowland, and the Yukagir plateau.

The MAATs in most regions have developed progressively during the three warming phases. The typical pattern involved a relatively slight rise in temperature between 1935 and 1945, some intensification between 1988 and 1995, and abrupt warming during 2002–2009. This was observed in the Lena sector of Middle Siberia and the northwestern and Far East sectors (see Table 3). Mean departures of the annual air temperature between the first two phases ranged from +0.1 °C (the Lena sector) to +0.5–0.6 °C (northeastern and Far East sectors), and those between the second and third periods were from +0.5 °C (Lena sector) to +1.1–1.2 °C (northeastern and Far East sectors).

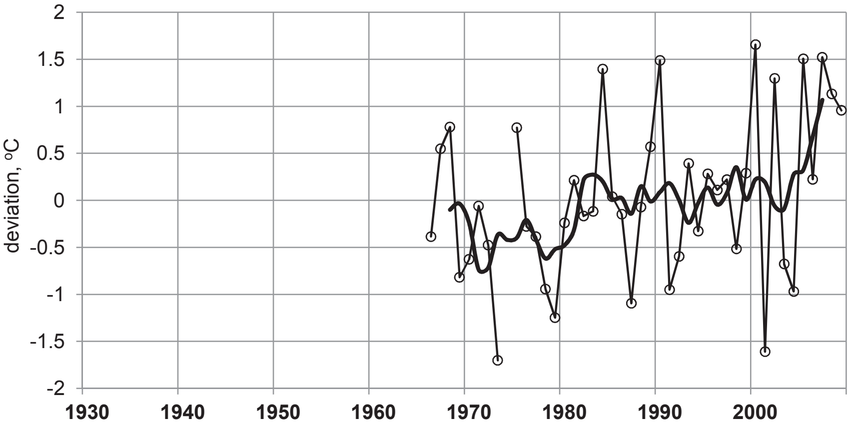

Fig. 5. Generalized model of the variation in the 1.6-m mean annual ground temperature departures in the Lena sector of the tundra-forest and northern taiga.

In the Yenisey part of Middle Siberia, the wave of warming (+0.4 °C) between 1988 and 1995 did not reach the level experienced between 1935 and 1945 (+0.8 °C) in tundra-forest, whereas in northern taiga, an increase of +0.5 °C was observed. Furthermore, an increase in temperature occurred in tundra-forest, as in other regions of the tundra-forest and northern taiga. In the tundra-forest and northern taiga, no increase in temperature was observed between the second and third warming phases, a pattern that is generally characteristic of the southern areas of Middle Siberia.

Changes in the freezing index occurred in a roughly similar pattern. However, it should be noted that whereas mean departures in the freezing index during 1935–1945 were about −50 °C*days in the tundra-forest and northern taiga of northeastern Siberia and the Far East, during 2005–2009 they reached −300 °C*days, or 5–6% of the mean value of the index.

Greater significant changes occurred in the thawing index between 2005 and 2009. The mean value in this phase reached +13%, whereas in the first two positive phases the mean value was about +2%.

For the Lena and northeastern sectors of tundra-forest and northern taiga, ground temperature data measured at meteorological stations are available for various depths. To construct generalized models of ground temperature for these sectors, we selected data from only those stations where significant correlations between stations were recorded. These were Olenek, Kyusyur, and Sukhana (Fig. 5), and Srendekolymsk (up to 1996 only), Delyankir, and Ust'–Moma (Fig. 6).

Despite such significant changes in the climatic characteristics, the response of ground temperatures was not equally pronounced. For example, in the tundra-forest and northern taiga of the Lena and northeastern sectors, MAGTs remained within the normal range

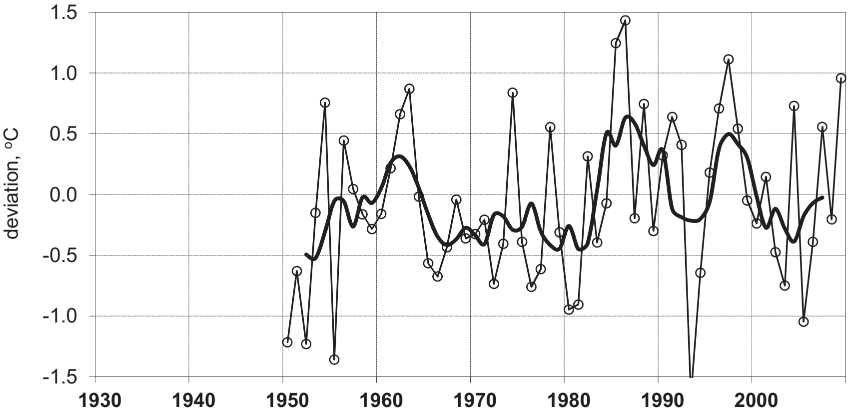

Fig. 6. Generalized model of the variation in the 1.6-m mean annual ground temperature departures in the northeastern sector of tundra-forest and northern taiga.

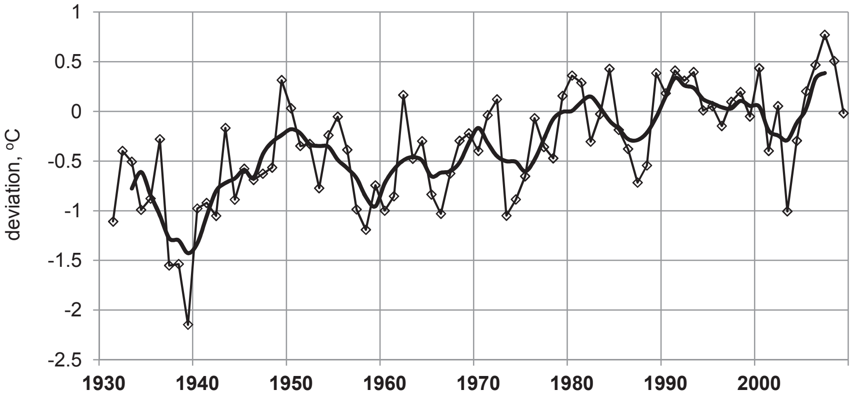

Fig. 7. Generalized model of the variation in the 3.2-m mean annual ground temperature departures in the central Yakutian sector of middle taiga.

between 1988 and 1995, while the increase in air temperature was relatively large. This was related to the pattern of snow accumulation, as the early-winter snow depth during this period was less than the long-term mean. The relatively low ground temperatures promoted stabilization of the thawing depth during this period. Between 2005 and 2008, snow depths in the northeastern sector were also below normal levels, as indicated by meteorological station data (Delyankir, Srednekolymsk, and Ust'–Moma), and this prevented ground warming (the departure in MAGT at 1.6 m was about 0 °C).

In the Lena and Yenisey sectors of the tundra-forest and northern taiga, the ground temperature departures between 2005 and 2008 were the maximum for all of northeastern Eurasia, averaging +1.1 °C.

4.3. Middle taiga landscapes on continuous permafrost (central Yakutia)

These landscapes are quite diverse and are located in the center of the study region. This is why the central Yakutia region is very important for understanding the general processes involved in the response of permafrost to climate change.

During 1935–1945, central Yakutia was a boundary between the warming north and the cooling south, with a mean MAAT departure of 0 °C. During 1988–1995, the area was at the forefront of warming (+1.0 °C), joining the then-warming south. When the center of warming shifted to the north again, during 2005–2008, central Yakutia joined the warming north and became a buffer for the now-cooling south. Thus, the changes in the MAAT and thawing index indicate that an enhancement of warming has occurred here with each positive warming phase.

Departures in the freezing index for the two last positive phases reached −5% during 1988–1995 and −7% during 2005–2009. The thawing index varied by ±1% during the first two phases, whereas during 2005–2009, it rose abruptly to +9%.

A generalized model of the variation in the departure of MAGT at 3.2-m depth for central Yakutia was constructed based on data from the Pokrovsk, Isit', Churapcha, Namtsy, Ytyk–Kyuel', Krest–Khal'dzhai, and Yakutsk stations (Fig. 7), which were well correlated with one another. Data from the Yakutsk station after 1963 were discarded because of the relocation of the measurement site and anthropogenic influences.

Ground temperature at 3.2-m depth responded to changes in air temperature only between 1935 and 1945, when values close to the normal departure were −1 °C, which was probably related to snow cover in the first half of winter. During that period, the mean December snow depth was 20% below the normal level. The MAGT departures during the subsequent positive phases were +0.2 and +0.4 °C, which were accompanied by increased thawing depths.

Our observations of thermokarst development in central Yakutia confirm that it is during these two positive phases that surface subsidence was activated (Fedorov and Konstantinov, 2003, 2008; Fedorov et al., 2012). The positive phase during 2005–2009 was associated with abrupt changes in the geocryological conditions of central Yakutian landscapes, together with abundant precipitation (Iijima et al., 2010). In general, these phases created a critical situation in disturbed and open sites and anthropogenic landscapes situated on the ice complex. This is related to the formation of hummocky polygonal landforms and the development of thermokarst lakes. At the Yukechi site, the surface area of young thermokarst lakes increased

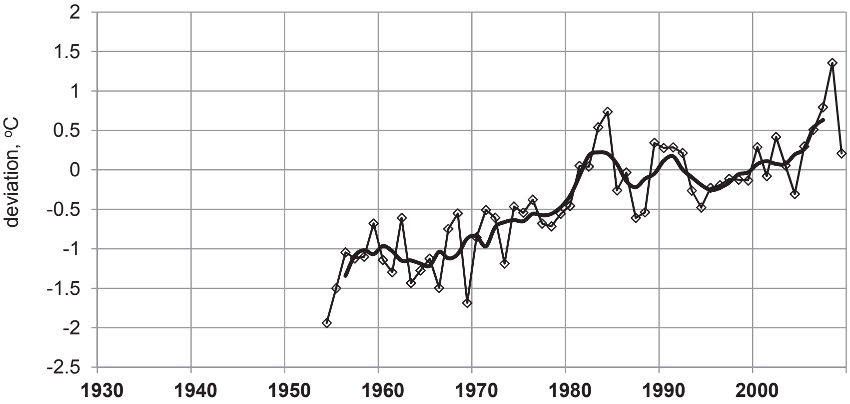

Fig. 8. Generalized model of the variation in the 3.2-m mean annual ground temperature departures in the Lena sector of middle taiga with discontinuous and sporadic permafrost.

fourfold during the period between 1980 and 2012, and new lakes are actively forming. Degradation of the ice complex provides up to one third of the water input in the water balance of such lakes (Fedorov et al., 2013). Using satellite imagery, Kravtsova and Bystrova (2009) found similar changes in the Vilyuy River basin.

4.4. Middle taiga and mountain taiga landscapes on discontinuous and sporadic permafrost

These landscapes border the study region of northeastern Eurasia in the south and represent seasonally frozen ground and isolated permafrost zones. They are also subject to various fluctuations under the influence of climatic changes.

In the period 1935–1945, these landscapes were outside the zone of warming, which, as the name implies, was within the Arctic zone. MAAT departures were 0 to −0.4 °C. The zone of decreasing temperatures was directed from west to east and south. Between 1988 and 1995, the landscapes under consideration were in the epicenter of change (+0.9 to +1.3 °C), with the change diminishing from west to east and from north to south. Although the next phase of warming (2005–2009) was maximal in all areas of northeastern Eurasia, warming here was weaker than during the previous phase. This is a specific feature of the landscapes under study in this region.

Departures of the freezing index for the positive phases were as great as +4% between 1935 and 1945, −9 to −10% between 1988 and 1995, and −5 to −8% between 2005 and 2009. The distinguishing feature in the development of these landscapes is the increased thawing index during the third phase of warming (2005–2009). While mountain taiga experienced uniformly increasing summer temperatures, middle taiga experienced an abrupt increase from 1–2% during 1935–1945 and 1988–1995 to 6–7% during 2005–2009.

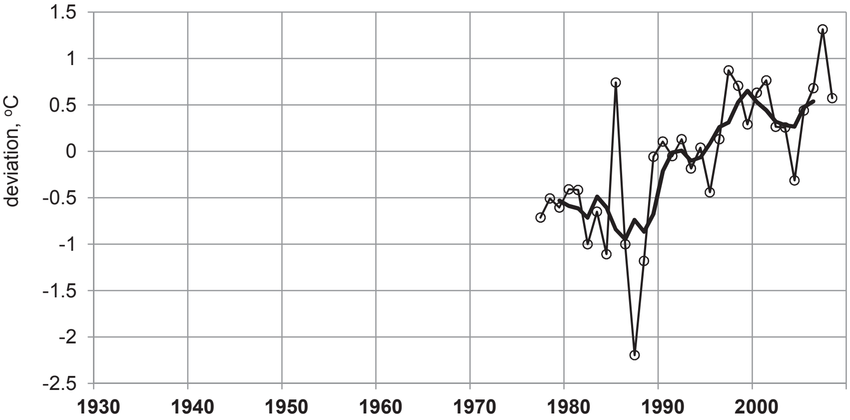

Fig. 9. Generalized model of the variation in the 1.6-m mean annual ground temperature departures in the Lena sector of mountain taiga with discontinuous and sporadic permafrost.

The model developed using data from the Olekminsk, Tommot, and Uchur stations characterizes the variability of ground temperatures at 3.2-m depth in the middle taiga, which is underlain by discontinuous and sporadic permafrost (Fig. 8). The model derived from the data from the Chara, Ust'–Nyukzha, and Sosnovo–Ozersk stations shows ground temperature variability at a depth of 1.6 m in the mountain taiga (Fig. 9).

Departures of ground temperature at a 1.6-m depth in the middle taiga were in the range of −0.1 to −0.2 °C during 1988–1995, and in the next phase (2005–2009), they increased to +0.6 to +0.7 °C. In the Far East sector, the increases were +0.3 °C and +0.8 °C, respectively. Changes in the freezing depth mainly followed changes in the ground temperature, and in general, there was a decrease in its thickness.

5. Conclusions

Increased activity of thermokarst processes was observed in northeastern Eurasia as a result of climate warming. Disturbed permafrost landscapes on ice-rich permafrost are particularly sensitive to warming. These include cut and burned areas, farmlands, and settlements. Thaw lakes are expanding rapidly and are affecting the surrounding terrain.

An analysis of three warming periods over the last eighty years has shown that the warming experienced during 1935–1945 and 1988–1995 varied. The greatest impact of warming was observed in tundra landscapes during the Arctic warming period between 1935 and 1945. In the 1990s, the center of the warming shifted to southern areas of northeastern Eurasia, and in the 2000s, the effect was observed everywhere. The rate of warming also differed among the three phases. However, it should be noted that both the magnitude of warming and its spatial coverage have increased during each phase. Climate change during the last warming phase (2005–2009) is of major concern because a strong loss of winter cold was observed, with the freezing index 7–10% below normal. Summer heat increased by up to 9–16% throughout the study region, and in the tundra zone of northeastern Siberia and the Far East, the increase reached 30–56%. Departures in the MAAT were 0.7–1.8 °C above normal.

These changes in climate have evidently resulted in changes in permafrost landscapes. Many areas in the continuous permafrost zone have experienced ground warming and seasonal thaw deepening. Shallower freezing in unfrozen ground is observed in areas of discontinuous and sporadic permafrost. This has resulted in increased activity of cryogenic processes, from thermal abrasion of the Arctic coasts to thermokarst and thermal erosion in southern areas of northeastern Eurasia. The high thermokarst activity observed recently throughout the region, resulting in hummocky polygonal relief on the ice complexes (yedoma), is compelling evidence of changes in permafrost.

Acknowledgments

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