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The Thermal Regime of Soils in the North of Western Siberia

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ABSTRACT

The results of long-term stationary observations upon the thermal regime of soils in natural and anthropogenically-disturbed tundra and northern taiga landscapes in the north of Western Siberia are discussed. Quantitative assessments of the heating effect of snow cover and the cooling effect of surface organic layer on soil temperatures in both winter and summer seasons are given. Spatial and temporal variations in the depth of seasonal thaw and soil temperatures in the tundra and taiga zones are outlined. Data on changes in soil temperature regimes following disturbance of surface organic layers are presented. Contemporary tendencies in permafrost degradation induced by climatic warming, changes in the snow cover depth, and anthropogenic impacts are shown. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: active layer; permafrost; seasonal thawing; thermal regime of soil

INTRODUCTION

A detailed monitoring of soil temperature conditions has been performed at geocryological experimental stations in the north of West Siberia since 1978 (the Marre-Sale station, western Yamal Peninsula) and 1972 (the Nadym station). The Marre-Sale station is located in the tundra zone with continuous permafrost; the Nadym station lies in the northern taiga zone with discontinuous permafrost (Figure 1). These stations form the basis for permafrost monitoring in the areas of active development of the oil and gas fields and pipelines in the Arctic and subarctic regions of Western Siberia. The Marre-Sale station is suitable for background monitoring, as it is beyond the area of direct industrial impacts. The Nadym station includes several observation sites located between 8–20 km along the Nadym–Punga gas pipeline.

The observation network at these geocryological stations consists of several experimental sites and profiles. At present, these stations have long-term (up to 30 years) continuous records of permafrost temperatures and the depth of seasonal thawing. These data can be used for long-term geocryological forecasts. In this paper, we analyse the spatial and temporal variability in the active layer and the permafrost temperatures in relation to variations in the main natural factors, including meteorological, geomorphological, and geobotanic conditions. In contrast to previous publications on this problem (Pavlov *et al.*, 1989; Dubrovin *et al.*, 1996; Pavlov, 1998; Moskalenko, 1999), we consider longer records of meteorological and geocryological data (up to 1999); for the first time, the data obtained at two different stations are analysed simultaneously.

METHODOLOGY

Several factors were taken into account when choosing the localities for geocryological stations: these included the morphology and temperature of permafrost (i.e. its depth, continuous or discontinuous character, etc.), the geology of the upper Quaternary deposits of the area, the character and activity of

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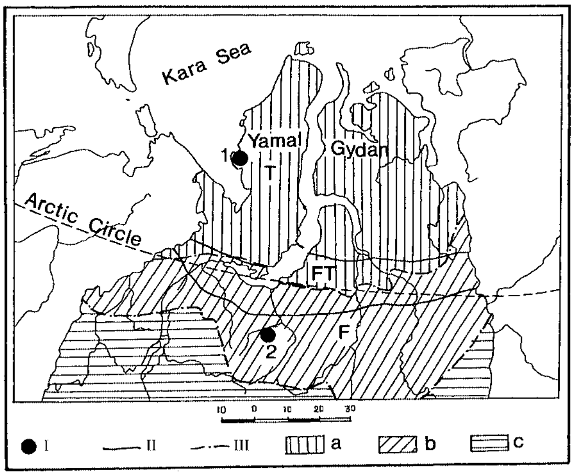

Figure 1 The location of geocryological stations in the north of Western Siberia. (I) Stations (1—Marre-Sale; and 2—Nadym). (II) Boundaries of natural zones (T—tundra; FT—forest-tundra; and F—taiga forest). (III) Boundaries of permafrost zones: (a—continuous; b—discontinuous; and c—isolated).

geocryological processes, the current meteorological conditions and the location of the nearest weather stations, the terrain conditions, and the expected type of technogenic impacts (Melnikov *et al.*, 1992). The particular places of observation sites were selected with due account of the results of the earlier geological surveys and the preliminary field and aerovisual investigations. Natural complexes (landscapes) of different hierarchical levels (from landscape facies (the lowest taxa) to landscape areas) are the main objects of stationary geocryological studies.

The Marre-Sale station is found on the Kara Sea coast, near the weather station of the same name. The terrain monitored lies within the third sea terrace (coastal plain). The relief of this plain is characterized by the predominance of gently undulating slopes complicated by erosional cliffs, deep gullies and the valleys of small rivers and creeks. The absolute height ranges from 0 to 40 m a.s.l. The near-surface sediments consist of loamy sand and sand overlain by peat (0.1–0.7 m thick) in some places. The vegetation cover is represented by the dwarf shrub–moss–lichen tundra alternating with mossy mires in local hollows. Disturbed areas are covered by secondary plant communities with the predominance of cotton grass and gramineous plants.

The Nadym station is found in the marginal part of the third lacustrine–alluvial plain, 30 km to the south of the town of Nadym, where the nearest weather station is located. Absolute height ranges from 30 to 40 m a.s.l.; the plain represents a levelled or slightly undulating surface complicated by small mounds and ridges due to cryogenic heaving. Better-drained sites along river valleys are covered by forests; mires and small lakes predominate on the central parts of interfluves. The plain is composed of lacustrine–alluvial sand with lenses and laminae of loamy sand and silty loam. Peat deposits up to 5 m thick and peat bog soils predominate in central parts of the interfluves. Zonal vegetation is represented by birch–larch and birch–pine forests with dwarf shrubs and lichens as the ground cover; sparse larch forest with dwarf shrubs and mosses occupy well-drained sites near river valleys; in areas subjected to frost heave, sparse cedar (*Pinus sibirica*) forest with wild rosemary–lichens and wild rosemary–sphagnum–lichens as the ground cover predominate. Isolated permafrost bodies are confined to sites occupied by peatlands, to frost-heaved mounds, and to areas with peat bog soils having a thick peat layer.

In the years of exploitation of the Nadym–Punga gas pipeline, the zone of strong disturbance around this pipeline extended from 50 to 200–400 m. This zone is characterized by the active development of various exogenous geological processes. The narrowest zone of disturbance is observed in the well-drained areas composed of sand. In areas occupied by peatlands and mires, the zone of disturbance around the pipeline reaches its maximum width. Between 15 to 20 observation sites in natural and disturbed conditions and between 40 to 60 observation boreholes were established at both experimental stations. Most of the boreholes were drilled along transects characterizing the main natural complexes. Up to 1996, temperature measurements at the Marre-Sale station were performed all year round; at the Nadym station, measurements were performed during the summer months. In the last five years, measurements at the Marre-Sale station have been performed only at the end of the warm season (i.e. in August and September).

The programme of thermal monitoring included: (a) soil temperature measurements (from the soil surface to a depth of 10–15 m), (b) the study of active layer, (c) the study of heat fluxes in the soil, and (d) the study of soil thermal properties (Melnikov *et al.*, 1992; Pavlov, 1983). The frequency of measurement varied from four times every 24 h (soil surface temperature, heat fluxes in soil) to one–three times per month (depth of thawing, temperature in deep layers). Special observations upon the snow cover depths in different landscape conditions, the development of cryogenic processes, lake-ice conditions, and the dynamics of biota were also performed. Detailed geobotanical descriptions were made at special test sites; these descriptions included data on the species composition of phytocenoses, the abundance of particular species, their life forms, average height of plants, the percent cover, and the frequency of occurrence of particular plants in the territory (Moskalenko, 1999). Large-scale mapping of the territory of experimental stations was performed repeatedly (every two–four years) with the use of aerophotos of 1 : 1000 to 1 : 5000 scale. The data obtained at the nearest weather stations were also used for the analysis of permafrost monitoring data.

RESULTS

Meteorological Conditions

Meteorological conditions of the geocryological stations (long-term averaged data) are given in Table 1. The period with negative (subzero) air temperatures lasts for 7.5–8.0 months. The sum of positive air temperatures in summer months (the thawing index, I_{th}) at the Marre-Sale station does not exceed 28 °C per month; at the Nadym station, the thawing index is two times higher because of the more southern position of this station and the higher input of solar radiation. Mean annual precipitation in Nadym is 1.5–1.6 times higher than at Marre-Sale; the snow cover in Nadym is also much thicker than at Marre-Sale (Table 1). It is known that snow depth is characterized by considerable spatial variability and depends on particular relief conditions. This is especially true with respect to tundra zones with rugged topography. Often, the snow cover is virtually absent on elevated elements of the relief, whereas its depth in adjacent depressions can exceed 2–3 m. Owing to strong winds, the snow cover in the north of Western Siberia is characterized by considerable compaction: the bulk density of snow changes from 180–260 kg/m^3 in the middle of November to 280–370 kg/m^3 in the period with the maximum snow depth.

For the period of permafrost monitoring (1972–1999), the curves characterizing mean annual air temperatures (for separate years) and thawing indices (I_{th}) at both stations generally agree with one another, despite the considerable distance between these stations. It is interesting to note that considerable deviations of these curves from corresponding mean (long-term) values are observed in the same years. Thus, at the Marre-Sale station, seven relatively warm (i.e. warmer than the 'norm') years can be distinguished on these curves (1976, 1981, 1984, 1989, 1993, 1995, and 1996); the years of 1972, 1978, 1979, 1992, 1998, and 1999 (six years) were cooler than the 'norm'. Starting from the mid-1960s, a general tendency for warming has been observed all over the northern regions of Russia. In the last 30–35 years, the increase in mean annual air temperatures in the northernmost part of Western Siberia constitutes about 0.8–1.6 °C. This increase is mainly conditioned by warmer temperatures of the winter period, the duration of which in the studied regions is two times longer than the duration of the summer period. The increase in mean annual air temperatures in 1965–1995 comprised 0.03 °C/year at the Marre-Sale station and 0.07 °C/year at the Nadym station. Data from weather stations show that there is no reliable correlation between the increase in air temperatures and the latitude of the place. It is interesting to note that 1995 was the warmest year in the north of Western Siberia, as well as in many other regions of the Northern hemisphere. Afterwards, a tendency for a decrease in

Table 1 Meteorological conditions and geocryological (i.e. ground temperature) observations in the north of Western Siberia at Marre-Sale and Nadym.

Indices	Station	
	Marre-Sale	Nadym
Mean air temperature (t_a), °C:		
annual	−8.0	−5.9
summer	4.7	10.8
winter	−14.4	−14.2
Annual amplitude of air temperatures, °C	29.0	40.5
Dates of temperature transition through 0 °C in:		
spring	Jun. 10	May 27
fall	Oct. 5	Oct. 20
Precipitation, mm:		
annual	301	483
in liquid form (rain)	135	237
Snow cover:		
date of occurrence	Oct. 10	Oct. 15
date of disappearance	Jun. 11	May 27
depth (April), m	0.29	0.76
average bulk density (April), kg m^{-3}	340	290
Mean annual ground temperature, °C	−2 to −7	+1 to −3

the mean annual air temperature has been observed (in 1998, the mean annual air temperature was 2.2–2.8 °C below the climatic norm). The period of 1965–1999 was also marked by a tendency towards an increase in precipitation in maritime regions (Marre-Sale) and a decrease in precipitation in continental regions (Nadym). In Western Siberia, the decade of 1975–1984 was marked by the snowiest winters. In general, the mean annual amount of snow within the last 20–25 years has increased by 5–15%.

Systematization of Data on the Thermal Regime of Soils

The active layer and permafrost temperature can be used as indicators of periodical variations and long-term trends in meteorological conditions. These parameters are dictated by air temperatures, the snow depth, vegetation conditions, and other environmental factors.

The Marre-Sale Station.

On average, the mean summer (June–September) temperature of the soil surface (t_s) on horizontal sites varies from 5.1 to 9.5 °C. Maximum monthly temperatures reach 13–15 °C (July). The ratio of the soil surface temperature to the air temperature (t_s/t_a) constitutes about 1.2–1.6 (with deviations from 1.14 to 2.05). Approximately the same values of this ratio have been obtained from data of weather stations located in coastal regions of the Russian Arctic. On slopes of southern aspect, soil surface temperatures are 1.0–1.3 °C higher than on slopes of northern aspect. The lowest temperatures are observed in the bottoms of gullies and river valleys (1.2–2.7 and 0.3–1.1 °C lower than on the slopes of southern and northern aspects, respectively) (Dubrovin *et al.,* 1996). At a depth of 0.1 m, the mean summer soil temperature (t_{01}) is twice as low as the soil surface temperature (Table 2). The maximum temperature at this depth is observed in the August. Sandy soil (site 7) is 2–4 °C warmer than peat soil.

The depth of seasonal thawing (h_{th}) varies from 0.4–0.75 m (on polygonal peatlands, palsa bogs) to 1.5–1.8 m (on deflated sand areas with fragmentary vegetation cover) (Table 3). The depth of thawing of floodplain soils and the soils of hollows connecting thermokarst lakes is about 0.8–0.9 m. Somewhat deeper thawing (up to 1.3 m) is observed in the bottoms of open hollows with flowing water and fragmentary development of peaty soils. On average, the active layer in the vicinity of the station varies from 0.8 to 1.1 m (for different years). The cooling

Table 2 Air temperature (t_a) and soil temperatures at the surface (t_s) and at a depth of 0.1 m (t_{01}) at the Marre-Sale station (1981–1993), °C. Maximum monthly temperatures for the long-term period are given in parentheses.

Site no.	Site description	Temperature	Months				Mean data		
			Jun.	Jul.	Aug.	Sep.	Jun.–Sep.	Oct.–May	Year
1	Weather station	t_a	2.2	7.7	7.1	3.8	5.2	−14.2	−7.8
2	Flat drained polygonal surface with cloudberry–polytrichum–sphagnum vegetation	t_s	4.4	9.7 (15.2)	8.1	3.2	6.4	−9.7	−4.3
		t_{01}	−0.1	3.1	5.0 (7.3)	2.6	2.7	−8.8	−5.0
2[d]	Similar to plot 2, but with disturbed vegetative cover	t_s	4.9	11.0 (17.7)	8.5	3.8	7.1	−9.9	−4.2
		t_{01}	−0.1	3.4	5.9 (7.5)	2.9	3.0	−9.5	−5.3
7	Gentle slope of southern aspect with windblown sands and sparse forb–dwarf shrub vegetation	t_s	6.6	12.6 (17.7)	9.5	3.9	8.2	−11.9	−5.2
11, 14, 15	Flat drained surface with dwarf shrub–lichen vegetation	t_s	4.5	11.4 (14.5)	9.1	3.6	7.2	−9.7	−4.1
12, 13	Tussocky drained surface with forb–dwarf shrub–moss–lichen vegetation	t_s	5.6	12.0 (16.9)	8.8	3.4	7.5	−9.9	−4.1
		t_{01}	1.7	5.0	6.3 (8.4)	3.0	4.0	−9.8	−5.2

Table 3 The depth of soil thawing (h_{th}, m) on the 15th day of each summer month at the Marre-Sale station (1979–1994).

Site no.	Site description	Soil	Characteristics of h_{th} value	Months			
				Jun.	Jul.	Aug.	Sep.
1	Polygonal surface with sedge–dwarf willow–green moss vegetation	Silty sand	*Mean*	0.27	0.66	1.08	1.23
			Max	0.41	0.93	1.30	1.37
			Min	0.16	0.43	0.88	1.05
2	Polygonal surface with cloud-berry–polytrichum–sphagnum vegetation	Peaty loamy sand	*Mean*	0.18	0.44	0.68	0.82
			Max	0.40	0.85	0.99	1.11
			Min	0.02	0.25	0.46	0.62
4	Sedge–hypnum moss mire	Peat loamy sandy	*Mean*	0.12	0.29	0.50	0.62
			Max	0.25	0.42	0.67	0.73
			Min	—	0.16	0.30	0.46
7	Gentle slope of southern aspect with windblown sands	Silty sand	*Mean*	0.56	1.09	1.36	1.50
			Max	0.86	1.26	1.66	1.77
			Min	0.38	0.91	1.15	1.27

effect of the ground cover on soil is seen in the delay of soil thawing in comparison with the date of transition of air temperatures to above-zero values. This effect is especially well seen in the first half of the summer (June and July) and can reach 5 °C upon a ground cover thickness of 4–5 cm. The mean annual cooling effect of the ground cover (vegetation and litter) is estimated at 0.5–1.5 °C.

Year-to-year variations in the depth of seasonal thawing of peat layers and peat horizons underlain by sand and sandy loam are considerable, especially at the beginning of the summer period (more than 25%). For mineral soils, these variations are smaller. Thus, for sandy soil (site 7), they do not exceed 15%. The deepest soil thawing is usually observed in abnormally warm years (1984, 1989, etc.). Those years with abnormally low mean annual air temperatures are often marked by a minimum depth of thawing (1980, 1986, 1992, and 1999). The ratio of maximum to minimum depth of thaw (h_{max}/h_{min}) at the same sites constitutes 1.3–1.4 for sites with thick peat horizons and 1.1–1.2 for sites with thin peat horizons. Against this year-to-year background variation in the depth of thaw, a weak tendency towards its increase is observed when the full data set is analysed (Figure 2). For 1975–1995, an increase in the depth of season thaw at the Marre-Sale station comprised 0.5–1.1 cm/year (0.8 cm/year on average). The period from 1996 to 1999 was characterized by somewhat lower mean annual temperatures and summer temperatures. If these years are taken into account, the tendency for an increase in the active layer becomes less pronounced (0.6 cm/year).

The soil temperature at a depth of 10 m (t_{10}) at the Marre-Sale station varies from −2.2 to −7.0 °C, ranging from −4 to −6 °C in the most widespread landscape types. Higher temperatures ($t_{10} > -4$ °C) are typical of the bottoms of hollows and gullies, swampy hollows, and leeward slopes where the snow cover depth reaches 1.5–2 m (up to 5 m in some places). The thickness of the layer of annual temperature fluctuations in these sites is about 9–11 m, and the values of t_{10} are virtually equal to the temperature at the bottom of this layer (t_H). Annual amplitude of temperatures at a depth of 10 m (A_{10}) does not exceed 0.3 °C. The lowest temperatures at this depth ($t_{10} < -5$ °C) are observed within elevated parts of the interfluves with very sparse plant cover (e.g. windblown sands, bare tundra polygons) and on windward slopes, where the snow depth is less than 15 cm. Owing to strong soil cooling in the winter and considerable soil heating in the summer, these geomorphological positions are characterized by much higher annual temperature amplitudes at a depth of 10 m (A_{10} up to 2 °C, borehole 32). In general, the lower t_{10}, the higher A_{10} and the thicker the layer of annual temperature fluctuations (H). At low-temperature sites ($t_{10} = -6$

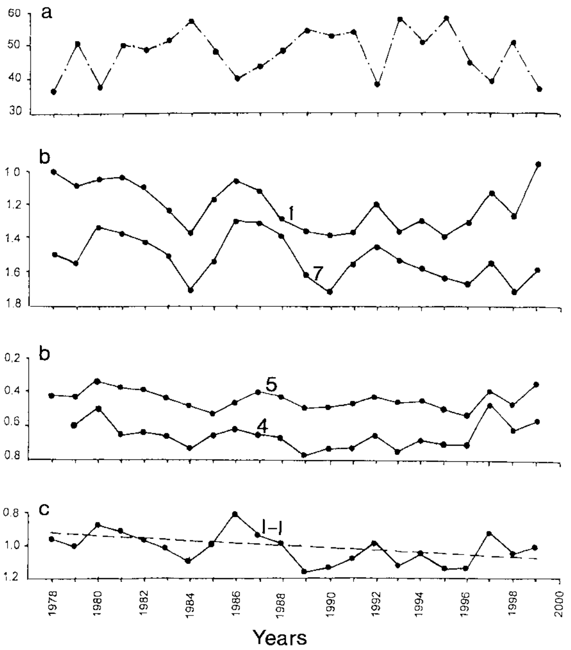

Figure 2 Changes in the (a) index of thawing $(^\circ\text{C·day})^{\frac{1}{2}}$, (b) depth of active layer (m), and (c) the ratio of active layer thickness to average values, 1978 to 1999, at the Marre-Sale geocryological station. Experimental sites: 1—polygonal tundra with the sedge–dwarf willow–green moss vegetation, 4—sedge–hypnum mire; 5—polygonal peatland with moss–lichen vegetation cover, and 7—wind blown sand on a gentle slope of southern aspect. I–I Averaged data from the main sites of the station; dashed line denotes the main trend.

to −7 °C), the thickness of this layer increases up to 15–18 m. The mean annual temperature at a depth of 10 m within polygonal peatlands varies from −5 to −6 °C; annual amplitude of temperature (A_{10}), from 0.8 to 1.3 °C; and the depth of the layer of annual temperature fluctuations, from 12 to 15 m. Considerable variations in t_{10} values are observed not only upon the transition from one type of landscape (geomorphological position) to another but also within relatively homogeneous landscapes. Thus, the range of variations in t_{10} is assessed at 1 °C for floodplains, 2 °C for peatlands and interfluves, and 2–3 °C for mires.

Temperature measurement data make it possible to estimate the heating effect of the snow cover on soils. At flat tundra sites with the snow depth about 0.2–0.3 m, the soil surface temperature (t_s) in the winter is, on average, 4.3–4.5 °C higher than the air temperature (t_a). In January and February, the difference may reach 10–12 °C. At sites subject to strong winds and thin snow cover, (e.g. site 7, Table 2), mean monthly differences between t_s and t_a (for the winter period) do not exceed 4 °C, being equal to 1–3 °C for the whole winter season. At most sites (e.g. sites 9, 32, and 36; Figure 3), a general tendency for an increase in soil temperature was observed between 1970–1995. The trend of soil temperature increase at a depth of 10 m is estimated at 0.01–0.07 °C/year. However, in 1996–1999, owing to the decrease in the air temperature, the soil temperature at a depth of 10 m also somewhat decreased.

The disturbance of the surface (i.e. the removal of vegetative cover, peat horizons, mixing and compaction of topsoil owing to caterpillar vehicle passages etc.) is accompanied by an increase in active layer thickness, surface subsidence phenomena, and the formation of water pools in micro-depressions. Upon a single vehicle passage, the depth of the active layer may increase by 15–40% within the first five to seven years. After this period, a partial restoration of initial vegetation conditions takes place and the active layer thickness decreases gradually towards initial values. Upon regular surface disturbances, a two-fold increase in active layer thickness is observed within 13–15 years.

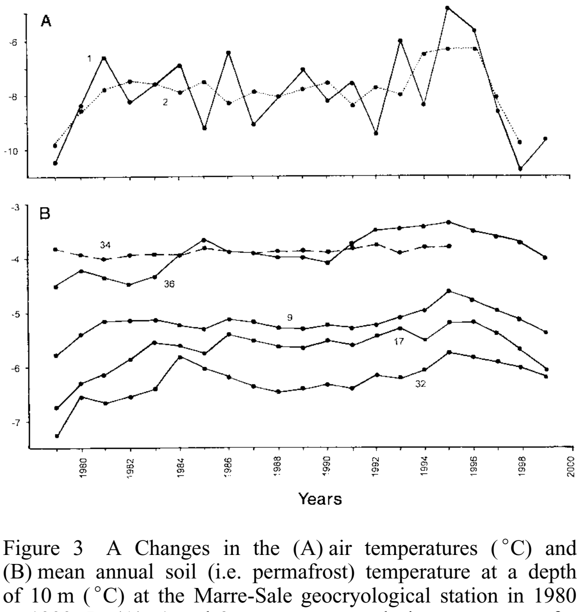

Figure 3 A Changes in the (A) air temperatures (°C) and (B) mean annual soil (i.e. permafrost) temperature at a depth of 10 m (°C) at the Marre-Sale geocryological station in 1980 to 1999. In (A), 1 and 2 are mean annual air temperatures for separate years and three- year running mean values, respectively. In (B), the experimental sites are: 9—gentle slope of western aspect overgrown by grasses and horsetail, 17—flat-topped peatland with dwarf shrub–moss–lichen vegetation cover; 32—polygonal tundra with moss–lichen–dwarf shrub vegetation; 34—draining hollow with cloudberry–sedge–sphagnum–moss bog; and 36—bottom of the hollow with sedge–moss vegetation.

The Nadym station.

In the warm season, the soil surface temperature (t_s) of peatland is close to air temperature. Thus, in July, when the soil surface temperature reaches its maximum, it is just 0.5–1.0 °C higher than the air temperature. For the whole summer, the difference is about 0.2 °C. In peat soils characterized by low thermal conductivity, temperature gradients within the active layer are considerable (Table 4). Thus, for 1972–1982, the average temperature gradient for the summer period in the upper 20 cm reached 3.5 °C/dm.

Table 4 Air and soil temperatures in an area of flat-topped peatland, Nadym geocryological station (1972–1982). Data in °C.

Depth, m	Months		
	Jul.	Aug.	Sep.
Air temperature			
	15.4	11.5	6.1
Soil temperature, undisturbed conditions			
0.0	15.9	11.8	6.0
0.1	7.0	6.3	4.2
0.2	4.2	4.8	3.5
Soil temperature, disturbed conditions			
0.0	15.5	11.9	6.8
0.1	10.4	9.5	5.8
0.2	7.5	7.9	5.4

Table 5 The depth of soil thawing (h_t, m) on the 15th day of each summer month at the Nadym geocryological station (1972–1983). Measurements made at (1) tussocks and (2) in the troughs between tussocks.

Peatland	Measurement point	Month			
		Jun.	Jul.	Aug.	Sep.
Natural (undisturbed) conditions					
Flat-topped raised bog	1	0.28	0.47	0.57	0.62
	2	0.23	0.38	0.47	0.52
Bog with small peat mounds	1	0.28	0.45	0.58	0.65
	2	0.24	0.4	0.54	0.61
Disturbed conditions					
Flat-topped raised bog	1	0.38	0.59	0.72	0.81
	2	0.33	0.57	0.68	0.81
Bog with small peat mounds	1	0.29	0.49	0.62	0.67
	2	0.28	0.46	0.57	0.61

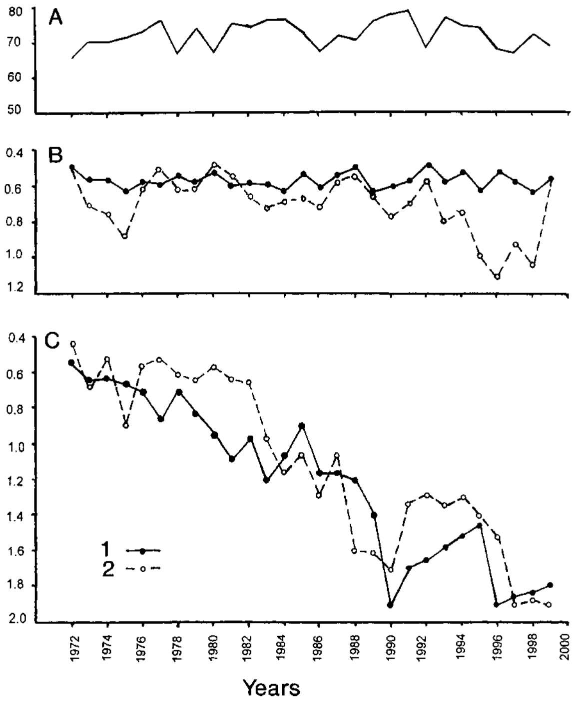

Figure 4 Changes in (A) index of thawing overtime (°C·day)$^{\frac{1}{2}}$, and (B) the active layer thickness (m) in natural (undisturbed) sites and (C) in disturbed sites, at the Nadym geocryological station, 1972–1999. 1—flat-topped peat bog; and 2—bog with small peat mounds.

The depth of seasonal thawing (h_{th}) within flat-topped peatlands with a peat thickness of up to 1 m ranged from 0.48 to 0.64 m (1972–1998); within hummocky peatlands having a less thick peat layer, it was somewhat greater (0.49–1.1 m). Deviations of h_{th} values from the mean within that period reached 25–30%. An increase in the active layer depth induced by climate warming is very low (Figure 4). At the same time, surface disturbances (i.e., the removal of plant cover and peat horizons, soil compaction, and topsoil mixing) are accompanied by a considerable increase in the depth of seasonal thawing and surface subsidence (Table 5). An increase in the thaw depth within disturbed flat-topped peatland in the first five to six years did not exceed 30% (Moskalenko and Shur, 1996). But in the ensuing years, especially 14–16 years after the disturbance, the h_{th} values increased by two to three times (in 1993) (Moskalenko, 1995). Such a significant increase in the active layer was caused by the melt of ground ice and some consolidation of the peat mass. This led to an increase in thermal conductivity of peat, the higher accumulation of solar energy in it, surface subsidence, and the development of water pools in disturbed areas. As a result, a secondary mossy mire developed in place of the flat-topped peatland; the permafrost table in the mire was at a depth of 1.8–2.0 m from the surface.

The mean annual soil temperature at a depth of 10 m in the territory of the Nadym station varies from −3 to +1 °C. The tendencies of temperature changes at this depth are somewhat different at different sites. Thus, within a thick peatland, the initial (1977) temperature t_{10} was −1.2 °C; 20 years later (1997), it was 0.6–0.8 °C warmer. The average increase in the mean annual temperature at this depth was about 0.2–0.6 °C; however, at the sites characterizing artificially drained peatlands, this temperature somewhat decreased in 25 years after drainage. The highest increase in t_{10} values (up to 2 °C) was observed at strongly disturbed sites along gas pipelines.

DISCUSSION

The contemporary increase in air temperature in the north of Western Siberia is estimated at 0.9 °C for the summer season, 1.4 °C for the winter season, and 1.2 °C for the whole year. Therefore, the effect of the summer season on current climatic warming is less pronounced than that of the winter season. From 1965 to 1999, the increase in mean annual air temperature was more pronounced in Nadym (northern taiga zone) than in Marre-Sale (tundra zone). Other meteorological data also support the conclusion that there is more active warming in middle latitudes as compared to high latitudes. It should be noted that the curves depicting multi-year variations in air temperature, precipitation, and the snow cover depth do not agree with one another.

The depth of seasonal thaw (h_{th}) depends on heat exchange processes of the summer period, whereas the mean annual temperature is mainly governed by winter processes (Pavlov, 1983, 1998). There is an evident correlation between h_{th} values and summer temperatures, especially in continental regions. It is generally believed that multi-year variations in the depth of the active layer (h_{th}) and soil temperatures in the upper permafrost layers are reliable indicators of contemporary climate change (Nelson *et al.,* 1993). For the Marre-Sale station, a general tendency for an increase in active layer (h_{th}) thickness was observed in 1978–1995. However, for the Nadym station, despite a more pronounced increase in air temperature during this period, an increase in the active layer was only observed for hummocky tundra sites. Long-term monitoring data obtained in the other regions of the north show that the active layer is not very sensitive to contemporary climate warming.

Permafrost temperature in the near-surface horizons is a more sensitive indicator of air temperature variations. A definite increase in permafrost temperature between 1975–1995 was observed both at Nadym and at Marre-Sale. This increase is most pronounced at the sites with colder permafrost. Thus, the increase in permafrost temperature was higher at the Marre-Sale station as compared to the Nadym station. At Marre-Sale, in its turn, the highest increase was observed in the low-temperature permafrost landscapes of polygonal tundra, whereas the minimal increase took place in relatively 'warm' sites on low floodplains and in river valleys. At sites where the permafrost temperature < -5 °C, the increase in this temperature comprised 0.7 °C (1975–1995); at sites where the permafrost temperature was above −3 °C, the rise was significantly lower (0.3 °C). The average rise in the permafrost temperature at the Marre-Sale station reached 0.03 °C/year, which is close to the actual rise in mean air temperature. The maximum rise in permafrost temperature can be expected in those years when the rise in air temperature is accompanied by a simultaneous increase in the depth of snow cover (i.e. in snowfall intensity). However, the patterns of temporal changes in winter precipitation and mean annual temperature are different. For instance, for the period from 1966 to 1999, the years with maximum snow depth were never the same as the years with highest annual temperatures.

Anthropogenic impacts on the terrain have a greater effect on the thermal regime of permafrost than the effect of natural climate change. At disturbed sites near the Nadym station, permafrost temperature at a depth of 10 m rose 0.6–0.8 °C within 25 years, and the depth of seasonal thaw increased by two to three times. At the Marre-Sale station, the increase in permafrost temperature within disturbed sites reached 0.2–0.9 °C (1980–1995).

CONCLUSIONS

The analysis of data obtained at weather stations in the north of Western Siberia shows a clear tendency for climate warming between 1965 and 1995. The average increase in mean annual air temperature during these years comprised about 0.03 °C/year at the Marre-Sale station and 0.07 °C/year at the Nadym station. The ensuing years (1996–1999) were relatively cold, though they did not change the general tendency for warming. This tendency is also manifested by an increase in the temperature of the upper permafrost horizons in response to climatic warming. The increase in rock temperatures at a depth of 10 m at the Marre-Sale station varied from 0.01 to 0.07 °C/year depending on site conditions. In some types of tundra landscape, the rise in permafrost temperature was even higher than the increase in air temperature. This is explained by an increase in the snow depth during the observation period. The response of seasonal thawing to climate warming is less pronounced than the response of permafrost temperature. Both soil and permafrost temperatures are also influenced by local anthropogenic disturbances to the ground surface. The study of the relationships between the impact of natural global climatic fluctuations on permafrost and the effect of diverse anthropogenic impacts on the environment of high latitudes is one of the top-priority problems of modern geocryology.

The expected continuation of global warming in the first half of the 21st century and the degradation of permafrost may cause significant adverse ecological and social consequences: these include the activation of cryogenic geological processes, a decrease in the strength of frozen soils under the bases of buildings, the deformation of buildings and other structures, and the destruction of natural–technogenic geosystems. The results of monitoring studies are necessary for detailed forecasts of the evolution of permafrost until 2025– 2050.

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