

AIR TEMPERATURE CHANGES AND THEIR IMPACT ON PERMAFROST ECOSYSTEMS IN EASTERN SIBERIA

by

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Significant increasing of mean annual air temperatures, freezing index and thawing index – have exerted a considerable impact on the state of permafrost landscapes and ecosystems in Eastern Siberia on the last few decades. Many animals and plants have shifted their ranges and this may be the precursor of northward shifts of the landscape zones. Landscapes that contain ground ice bodies in the underlying permafrost are especially sensitive to climate warming. Increase of mean annual air temperature for 2-3 °C over the last three decades has resulted an increase in ground temperature by 0.4-1.3 °C in the upper part of permafrost, which in turn has led intensification of negative cryogenic processes. Previous year's measurements of greenhouses gases emission in the Middle Taiga forest of central Yakutia were found to show high values and spatial variability. The wet meadow soils and shallow lakes have highest methane fluxes, almost comparable with emissions from tropical peatlands. Permafrost ecosystems respond to global warming quite rapidly. This makes the study of their changes somewhat easier, but still requires meticulous attention to observations, research, and analysis of the processes under way.

Key words: *air temperature, global warming, permafrost ecosystem, permafrost landscape, Eastern Siberia*

Introduction

Climate cycles that cause the periodic alternation of warming and cooling epochs play a great role in the development of life on Earth. They are associated with the major evolutionary events on Earth, including the appearance of free oxygen in Earth's atmosphere, the formation of natural zones and the movement of plants and animals onto land. The current state of the Earth's environment has to a large extent been shaped by the Quaternary glaciations which ended 12,000-18,000 years ago. Vast areas of frozen ground have survived on the Earth as a relict of the Pleistocene glaciations. Perennially frozen ground is estimated to occupy 22 million km² in the Northern Hemisphere, including 7.64 million km² of continuous permafrost and 14.71 mil-

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lion km² of sporadic permafrost. Russia has approximately 70% of its total land area, or over 11 million km², underlain by permafrost [1].

Current climate warming and air temperature changes have a strong impact on the natural environments. The global mean temperature has risen by 0.85 °C since the second half of the 19th century [2]. This phenomenon is especially notable in permafrost regions. The response of permafrost ecosystems to climate warming has been significant in recent decades. Landscapes that contain ground ice bodies in the underlying permafrost are especially sensitive. However, not all permafrost landscapes are equally sensitive to environmental changes; many have a capacity for resilience, which protects them against thermal degradation [3]. At the current level of warming, in Eastern Siberia, the sufficiently high resilience is characteristic for the taiga landscapes, which protect the underlying permafrost from degradation due to the sufficiently thick shielding layer lying between the active layer and the top of ground ice bodies. The permafrost landscapes where the shielding layer is thin and has already been transformed by disturbances, such as fires, forest harvesting, or surface modification, are highly sensitive to warming and anthropogenic disturbances.

Current state of permafrost in Eastern Siberia

Temperature variations under global climate change and their consequences for permafrost ecosystems will be discussed with reference to Eastern Siberia. Located here are the centre of the Eurasian continental permafrost zone and the largest administrative unit of Russia, Yakutia (fig. 1). The region has a severe, extremely continental climate with long winters 7-8 months in duration and short summers lasting 3-4 months. Mean annual air temperatures range from –6 °C to –14 °C, with January means of –29 °C to –48 °C and July means of +12 °C to +19 °C. The record low temperature is –72 °C and the highest temperature is +38 °C. The mean annual precipitation ranges from 180 to 680 mm [4]. Yakutia lies almost entirely within the permafrost zone. Over 80% of the region is underlain by continuous permafrost with thicknesses greater than 400 m [5]. The thickest permafrost, 1500 m, occurs in the Vilyuy River basin. In the continuous zone, permafrost is absent only beneath the rivers and lakes. The southern part of Yakutia is in the discontinuous permafrost zone where 40 to 80% of the ground is underlain by permafrost. The Vitim-Lensk area

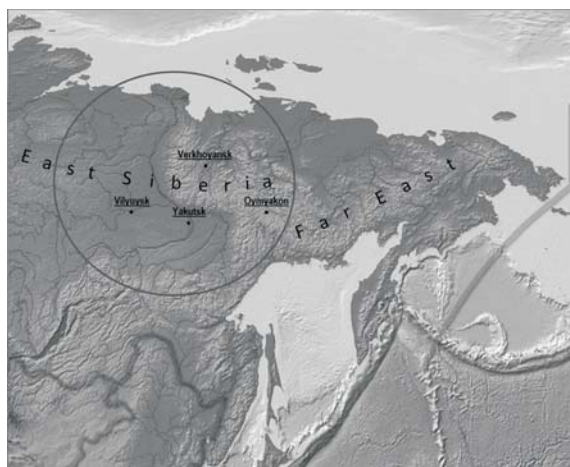


Figure 1. Location of the study region (circle – study territory)

in the far south-west of Yakutia has sporadic permafrost (10 to 40% of the ground underlain by permafrost). Permafrost thicknesses vary from 50 to 200 m in the discontinuous zone and from 10 to 50 m in the sporadic zone.

The formation of permafrost in Eastern Siberia began 2.5-3 Ma ago [6]. Since then, the regional permafrost has undergone numerous changes with colder and warmer periods. The last glaciations in Yakutia occurred during Sartan (12-25 ka) and Zyryan times (45-100 ka). These glacial episodes were associated with the formation of the so-called ice complex in the lowlands of northeastern and central Yakutia [7, 8]. During the Zyryan glaciation, the ice

complex formed in the region which was then dominated by tundra-steppe landscapes and had mean annual air temperatures of -14°C to -16°C . Around 37 ka, this glaciation was succeeded by the Karginik interglacial with mean annual temperatures of -12° to -14°C , but the ice complex did not degrade significantly during this time.

The Karginik interglacial was followed by the Sartan glaciation which began 26 ka and lasted until the Allerød (11.5 ka). The ice complex is defined as permafrost deposits that have a high content of ice wedges. Ice wedges are formed as polygonal networks due to freezing of water in thermal-contraction cracks. In the Arctic coastal plains and islands of Yakutia, ice wedges are 50-80 m in vertical extent, comprising 80-90% of the ice complex by volume, fig. 2 (a). In central Yakutia, ice wedges are 40-60 m thick and takes up to 50% by volume of the ice-complex material, fig. 2 (b).

Since we consider not only the active layer of soil, which includes only thawed layer, but also considering freezing, it is appropriate to use the term of *seasonally thawed and frozen layer*. Spatial variations in permafrost temperature, as well as in thicknesses of the seasonally thawed and frozen layers are controlled by landscape conditions. In general, thickness of the seasonally thawed layer and ground temperature decrease with increasing latitude. In Eastern Siberia, the coldest ground temperatures (-10 to -13°C) at 10-15 m depth and thinnest active layers (0.2 to 0.4 m) occur in the Arctic Tundra Zone. The Northern Taiga Zone is characterized by average ground temperatures of -4°C to -7°C and average thicknesses of the seasonally thawed layer of 0.6 to 1.2 m, whereas the Middle Taiga Zone has ground temperatures ranging from -2° to -4°C and seasonal thaw depths from 1.2 to 1.8 m. In the areas of discontinuous and sporadic permafrost of the Middle Taiga Zone, ground temperatures are from 0°C to -2°C and the seasonally frozen layer is 2-3 m thick. In mountains, ground temperatures and seasonal thaw depths in the continuous permafrost zone are controlled by altitudinal zonality: -9°C to -14°C at 0.3 to 0.8 m in the Alpine Desert Zone, -7°C to -11°C at 0.5 to 1.4 m in the Alpine Tundra, -3°C to -9°C at 1.5 to 1.8 m in the Subalpine Shrublands, and -3°C to -7°C at 0.8 to 1.8 m in the Mountain Open Woodlands. In the discontinuous and sporadic permafrost zones, in the Mountain Taiga, temperatures range from 0°C to -2°C in frozen ground and from 0°C to $+2^{\circ}\text{C}$ in unfrozen ground, the seasonally thawed and seasonally frozen layers are 3-4 m thick. Along with the Arctic Ocean ice cover, the cold mass accumulated in the permafrost of Yakutia as a sum of negative temperatures acts as a stabilizing factor against rapid climate changes on the planet.

Air temperature changes associated with global change

According to the IPCC, global climate changes have affected the Arctic and Subarctic areas greater than any other region on the Earth. In this respect, Eastern Siberia falls within the zone of strongest warming. Until the 1980, the region located in the center of the continental permafrost zone of the northern hemisphere experienced no significant change in mean air temperature (fig. 3). More serious changes in the climate of the East Siberian permafrost region have occurred since the mid-1980s. Gavrilova [9] pointed out that the current climate warming was largely due to warmer winters and that the climate trends varied notably across the region.

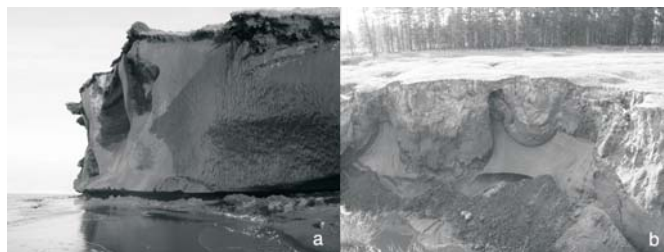


Figure 2. Ice complex exposures: (a) Laptev seacoast; (b) central Yakutia

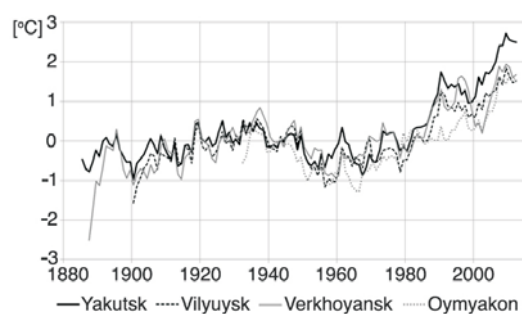


Figure 3. Deviations of mean annual air temperature for Yakutsk, Vilyuysk, Verkhoyansk and Oymyakon meteorological stations, five year running means

identified three positive phases in the climatic cycles, 1930-1939, 1985-1995, and 2005-2014, which were most typical for these meteorological stations and the whole region. Air temperature deviations were determined relative to the long-term means for the period 1930-2014 (tab. 1).

Skachkov [10] analyzed the spatial variation in mean annual air temperature (MAAT) trends in Yakutia over the period 1965-1995. His map shows that the north-western and far northeastern parts of Yakutia experienced the least warming, whereas the southwest and center of Yakutia had the greatest increase in MAAT. The same author [11] estimated that from 1966 to 2009 the MAAT increased by 3 °C at Yakutsk, by 2.2 °C at Vilyuysk, by 1.8 °C at Verkhoyansk, and by 2.2 °C at Oymyakon.

In order to compare the effect of present day climate change for the four meteorological stations under consideration we identified three positive phases in the climatic cycles, 1930-1939, 1985-1995, and 2005-2014, which were most typical for these meteorological stations and the whole region. Air temperature deviations were determined relative to the long-term means for the period 1930-2014 (tab. 1).

Table 1. Mean statistic characteristics MAAT, FI, and TI on meteorological stations (1930-2014)

MAAT						
N°	Station	Average annual [°C]	Std*	Var**	Trend [°C per year]	R ^{2***}
1	Verkhoyansk	-14.9	1.17	7.9	0.02	0.14
2	Oymyakon	-16.0	1.06	6.6	0.02	0.22
3	Vilyuysk	-8.8	1.28	14.6	0.02	0.12
4	Yakutsk	-9.6	1.28	13.4	0.03	0.31
Thawing Index						
N°	Station	Average annual [°C per day]	Std	Var	Trend [°C per year]	R ²
1	Verkhoyansk	1413	155.0	11.0	1.95	0.10
2	Oymyakon	1264	136.8	10.8	2.04	0.13
3	Vilyuysk	1796	143.1	8.0	1.99	0.12
4	Yakutsk	1943	128.3	6.6	1.58	0.09
Freezing Index						
N°	Station	Average annual [°C per day]	Std	Var	Trend [°C per year]	R ²
1	Verkhoyansk	-6898	356.6	5.2	4.91	0.12
2	Oymyakon	-7156	341.1	4.8	5.96	0.18
3	Vilyuysk	-5023	409.1	8.1	4.81	0.08
4	Yakutsk	-5497	410.3	7.5	9.67	0.34

* – standard deviation, ** – coefficient of variation, *** – coefficient of determination

In 1930-1939, deviations in the MAAT were relatively same, 0.4-0.5 °C. During the period 1985-1995, warming was stronger with the average deviation in MAAT being 1.2 °C for Yakutsk, 0.7 °C for Vilyuysk, 0.9 °C for Verkhoyansk, and 0.2 °C for Oymyakon, whereas in 2005-2014 the deviations were 2.5, 1.6, 1.8, and 1.5 °C, respectively.

The freezing index, or the sum of negative daily mean temperatures, which determines the stored cold resources and stability of permafrost, also varied. During the period 1930-1939, the freezing index deviated little, by -3% to +1%, from the long-term average, whereas during the warming phase in 1985-1995, the winters warmed by 3-4% at Vilyuysk and Yakutsk and by 1-2% at Oymyakon and Verkhoyansk. During the period 2005-2014, the resources of cold decreased by 5-6% at Verkhoyansk, Oymyakon, and Vilyuysk and by 10% at Yakutsk.

The thawing index, or the sum of positive daily mean temperatures, also showed variable trends. During the period of Arctic warming (1930-1939), summer temperatures were 6% higher than the long-term means in the northern regions (Verkhoyansk and Oymyakon), whereas in central areas of Eastern Siberia (Vilyuysk and Yakutsk) they were close to the normal (+1 to +2%). During the period 1985-1995, summer temperatures were within the normal or lower (-1% at Vilyuysk and Yakutsk, 0% at Verkhoyansk, and -3% at Oymyakon). The situation changed strongly during the last warming phase (2005-2014) when the magnitude of summer warming was as high as 9-15% (9% for Yakutsk, 11% for Vilyuysk, 13% for Verkhoyansk, and 15% for Oymyakon).

These changes in air temperature have obviously affected the development of permafrost ecosystems in Eastern Siberia. The permafrost warming, deepening of the active layer, and enhanced permafrost-related processes modify the landscapes and ecosystems.

Climate change effects on permafrost

In recent decades, significant changes have occurred in permafrost conditions. During the period 1965-2005, trends in mean annual ground temperature (MAGT) in Eastern Siberia were found to range from 0.01 to 0.03 °C per year [12]. The trends were highest in central Yakutia and lowest in the Arctic areas. Romanovsky *et al.* [13], who analyzed the ground temperature changes on the east siberian transect in Yakutia over the period from 1956 to 1990, observed a similar spatial distribution of the trends.

Rapid changes in the permafrost landscapes have been documented in the north of Eastern Siberia by several studies. For example, Morgenstern *et al.* [14] reported a high density of young thermokarst lakes on the ice complex (yedoma) with ice-rich deposits in the Lena delta, implying current thermokarst activity. Our observations in this region, at the CALM site near Tiksi, indicated significant thermokarst activity from 2004 to 2014 in the foothill low-centered polygonal tundra where ice wedges melted to depths of 1-1.5 m. Using satellite images taken in 1977 and 2010, Van Huissteden *et al.* [15] identified a threefold increase in the number of thaw ponds near Chokurdakh in the lower Indigirka area, as well as a significant expansion in their area. This suggests that significant permafrost degradation is occurring. Grigoriev *et al.* [16] reported that thermal erosion on ice-rich arctic coasts in Eastern Siberia is activated with increasing air temperature, and this occurred during the 1930s-1940s and the 1980s-1990s.

Data from the 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). According to data courteously provided by V. G. Rusakov, the MAGT at 10-m depth in Tiksi was 0.8 °C warmer during 2005-2014 compared with the pe-

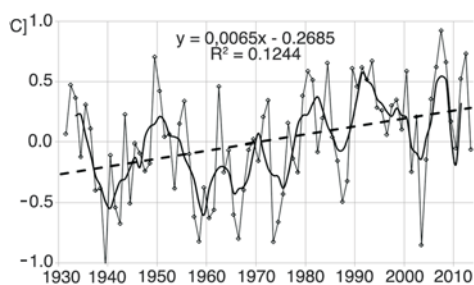


Figure 4. Generalized model of the variation in the 3.2 m MAGT deviations in the central Yakutia

Perevoz, Krest - Khaldzhay, and Isit weather stations (fig. 4). Some discordance between the graphs of air and ground temperatures is due to the effect of numerous factors that control the ground thermal regime. In central Yakutia, ground temperatures are strongly affected by snow cover. The warmer ground temperatures in the early 1980s and the 1990s, and in the second half of the 2000s and the early 2010s have played a significant role in changing the permafrost landscapes.

Our observations of thermokarst rates in central Yakutia confirmed that ground surface subsidence intensified during the recent decades [17]. The strong changes in the permafrost landscapes of central Yakutia were associated with increased precipitation and soil oversaturation in 2005-2007 under general climate warming [18]. In the whole, these phases created very critical situations in disturbed and open areas and in anthropogenic landscapes underlain by the ice complex. This is related to ground subsidence caused by melting of the tops of ice wedges and to the development of thermokarst lakes. On the Melnikov Permafrost Institute monitoring site at Yukechi, the area of young thermokarst lakes has increased fourfold between 1980 and 2012, new lakes are now actively forming at the site.

Several studies were undertaken to measure greenhouse gas fluxes from soils and lakes at different stages of thermokarst development (bylar, dyuedya, tympy, and mature alas) and to estimate their contribution to the accumulation of greenhouse gases in the atmosphere under increasing air temperatures [19-21]. The CO₂ emission was found to be higher from the forest soils, varying from 44 to 293 mgC/m²h, and lower from the meadow soils (37-249 mgC/m²h), CO₂ uptake was observed from the lake water surface (56 to -149 mgC/m²h). The CH₄ emissions were higher from pond surfaces, ranging from 654 to 8050 μgC/m²h. The highest methane emission was observed from a shallow lake at the dyuedya stage (8050 μgC/m²h in August). In forest soils, methane uptake was observed with values ranging from 5 to -34 μgC/m²h. The N₂O fluxes from all the study sites were low and varied within the range of -4 to 25 μgNm²h. The N₂O emission was greatest from the soil of wet meadow in the mature alas. The absolute values of soil CO₂ emission in the Middle Taiga of central Yakutia were found to show strong spatial variability, and the alas landscapes to be a significant source of methane. The wet meadow soils and shallow lakes have highest methane fluxes, comparable with emissions from tropical peatlands.

Climate change effects on biological resources

In recent decades, the length of the warm season has been increasing. Spring now arrives 10-15 days earlier and autumn ends 15-20 days later than they did in the mid-twentieth century. An analysis of long tree-ring chronologies from Central Yakutia spanning on average

riod 1993-2004, with the long-term mean being -10.9 °C. Records from the Verkhoyansk weather station show that ground temperatures at 1.6 m depth increased by 1.3 °C between these two periods, with the long-term mean being -7.2 °C.

In the middle part of Eastern Siberia, in central Yakutia, ground temperatures at 3.2 m depth were 0.1 °C lower in 1930-1939, 0.2 °C higher in 1985-1995, and 0.4 °C higher in 2005-2013 compared to the long-term mean of -2.6 °C averaged for the Yakutsk, Pokrovsk, Namtsy, Borogon, Churapcha, Okhotskiy

140-150 years found an earlier start of tree growth. The growing season of larch typically began in the end of May during the first half of the twentieth century, while over the last decades the timing has shifted to early May. For pine, the start of the growing season has advanced from middle May to late April. The main cause of the earlier tree growth is that the first date with an average daily temperature above 0 °C has shifted to the beginning of the third 10-day period of April with a concurrent increase in mean daily air temperature by 1-2 °C compared to the previous periods.

Changes in bioclimatic conditions affect the structure and status of biological diversity, as well as the distribution of plants and animals. Botanical studies indicate a steady increasing trend in the number of plant species. In this respect, the dynamics of vascular plant species diversity in Yakutia is representative.

The multi-purpose expedition organized by the USSR Academy of Sciences in the period 1925-1930, as well as other early studies identified 1190 species of vascular plants in Yakutia (fig. 5). The number of species increased to 1520 in the 1960s and to 1560 in the 1970s. By 2005, the number of vascular species was as many as 1965. Based on the most recent data available (2012), Yakutia has 1987 vascular species. This increase was primarily due to the intensification of botanical research. However, the recent inventories of flora in Yakutia do provide evidence for invasion of new species, the range of which did not previously extend beyond the Pre-Baikal and Trans-Baikal areas.

Warming strongly affects the natural habitats of animals, causing their range to expand northward. For example, in the 1960s, the northern limit of the range of red deer (*Cervus elaphus*) was along the river Lena up to the confluence with the river Olekma covering its basin, whereas today this species is encountered as far as the latitude of the river Aldan mouth, its range covering the entire Lena-Aldan watershed [27]. The same is observed for roe deer (*Capreolus capreolus*). While 150 years ago this species inhabited only the south-western-most part of Yakutia, today the roe deer is found throughout central Yakutia up to the latitude of Zhigansk (fig. 6). Improvement of the animal habitats not only affects the geographical ranges of animals, but also offers opportunities for new species to invade. For example, the current avifauna of Yakutia consists of 310 species of 19 orders of birds, including 258 migratory, 48 non-migratory and 38 vagrant birds. Since the early 1960s, 21 new migratory species and 27 vagrant species have been recorded in Yakutia [28]. It means that the avifauna of the region has increased by 47 species (18.8%, or almost 1/5 of the previous composition) since the 1960s.

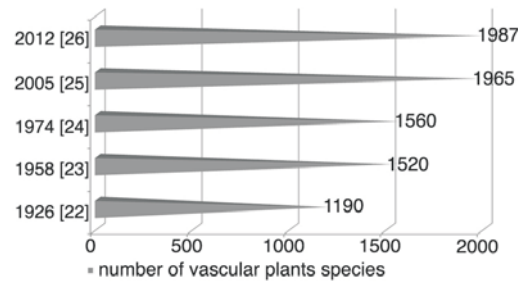


Figure 5. Changes in the number of vascular plants



Figure 6. Changes in the range of roe deer, in Yakutia during the last 150 years: 1 – 18th century [29], 2 – 1960s [30], 3 – 1970s [31], and 4 – sightings in the 1960s [30]

Changes in the environmental conditions have caused new pest insects to invade Yakutia in recent decades. In 2002, entomologists from the Institute for Biological Problems of Cryolithozone found the white cabbage butterfly (*Pieris brassicae* L.) in southwestern Yakutia near the border with the Irkutsk Province. This European species migrated first to Western Siberia and now its populations are found in Trans-Baikal and in the south of the Russian Far East region. This thermophilic species has been reported to expand its range northward along the warm river Lena valley. Massive occurrences of cabbage aphid (*Brevicoryne brassicae* L.) are observed in cabbage fields near Yakutsk. Increased rainfall has resulted in the appearance of land slugs belonging to the mollusks (presumably the field slug, *Deroceras agreste* L.) in farm fields and gardens (predominantly on cabbage plantations) in Central Yakutia which never occurred before due to its dry climate. The grain aphid (*Sitobion avenae* F.) has been reported to increase in number on cereal crops (wheat, barley, and oats) and perennial grasses which are likely related to increased wetness of the climate in Central Yakutia.

An unprecedented outbreak of the Siberian silk moth (*Dendrolymus superans sibiricus*) in 1999-2001 in Yakutia can also be attributed to climate change. The pest spread over the area of 5,000,000 ha, with the locus of outbreak covering 497,730 ha. The density of larvae increased to the maximum of 2309 individuals per tree, which was much higher than during the earlier outbreaks.

Thus, climate warming causes a gradual expansion of many species of animals and plants from south to north, which can be considered as the northward shift of the natural zones. The shift of the natural zones contributes to an invasion of new plant and animal species into the northern areas, including crop pests and pathogens.

Conclusions

Current changes in the climate, primarily increasing air temperatures, have exerted a considerable impact on the state of permafrost landscapes and ecosystems in Eastern Siberia. The 2-3 °C rise in mean annual air temperature over the last three decades has resulted in a ground temperature increase of 0.4-1.3 °C, which in turn has led to deepening of seasonal thaw and intensification of cryogenic processes. In forest-free and disturbed locations underlain by the ice complex, permafrost has begun to degrade resulting in thermokarst development and landscape reshaping. Permafrost degradation makes the land useless for agriculture and other purposes and poses a potential threat to human life and activities. Increasing air temperatures have triggered changes in the ecology of Eastern Siberia. Many animals and plants have shifted their ranges and this may be the precursor of northward shifts of the natural zones. In warming climate, cryogenic processes cause local redistribution of the ecosystems, which has not been understood adequately yet. Permafrost ecosystems respond to global warming quite rapidly. This makes the study of their changes somewhat easier, but still requires meticulous attention to observations, research, and analysis of the processes under way.

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