FCO UK-Russia Project

Assessing and communicating country level climate impacts in Russia and the UK

Summary report

Impacts of Changing Climate in Permafrost Regions: the Russian Perspective

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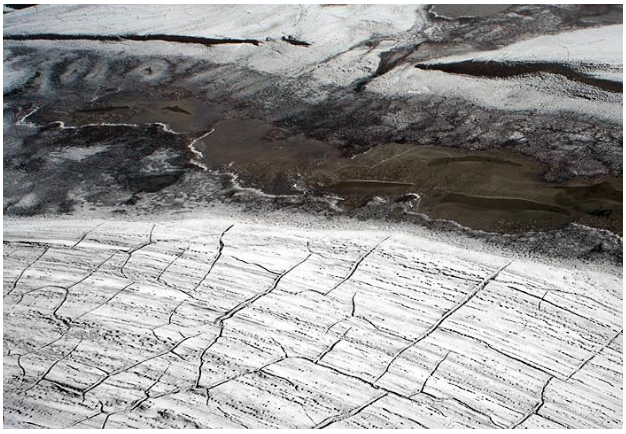

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Introduction

Although Russian scientists have been involved in major international climate assessment initiatives by WMO and Arctic Council since their start in early 1990s, until recently official Russia did not identify itself as an active player in climate adaptation and environmental policymaking. In 2008 Roshydromet made a step towards changing this situation to the better by publishing the first assessment report on climate change and its consequences in Russia (Бедрицкий et al., 2008a, b). Two volumes of this publication mirrored the IPCC assessment reports. The first volume was dedicated to the analysis of the ongoing and projected changes in the physical parameters of climate in Russia, while the second volume was focused on the impacts such changes may have on the economic sectors. Soon after the release of this report, Roshydromet prepared the so-called Climate Doctrine, which was officially endorsed by the Russian government in December 2009. It was the first-ever document presenting Russia's vision of the road map leading to the development of the national climate adaptation and mitigation strategies.

Implementation of these strategic tasks in Russian realms was difficult, first of all because of the climate skepticism dominating the Russian business community, policymakers and general public. Despite this difficulty, further efforts were made to put Russia in line with the other developed countries on climate change issues. In November 2011 Roshydromet and the Russian Academy of Sciences, in collaboration with the World Meteorological Organization and World Bank, organized an international conference "Problems of adaptation to climate change", the first time such a conference was organized in Moscow. The conference admitted the importance of the problem for Russia and formulated a three-fold task, (1) to narrow the uncertainty of climate prediction in Russian regions, (2) to assess the full range of impacts of climate change on the economy, natural, and human systems in Russia with a special focus on the identification of levels of warming leading to the optimal balance between climate mitigation and adaptation costs, and (3) to develop effective national adaptation strategies that would minimize the negative consequences for different climate-change thresholds. Through the present time, only a few of these tasks have been addressed at a sufficient level of detail and key findings were presented in the Second assessment report by Roshydromet in 2014 (Kattcov and Semenov, 2014)

This report is an initial part of the work on the UK Foreign and Commonwealth Office (FCO) funded Russia-UK collaborative project "Assessing and communicating country level climate impacts in Russia and the UK". The purpose of the project is to develop and apply advanced approaches for the assessment and synthesis of climate impacts at a national level in both countries to enable more consistent and transparent communication of key impacts and raise awareness of these among national and international stakeholders. For this project, Russia will focus on the magnitude of climate impacts on terrestrial permafrost. The results from this project will feed into the overarching initiative "Country Level Impacts of Climate Change (CLICC)" which was initially funded by the UK government and is now being taken forward by UNEP. Russia played an important role by undertaking a CLICC pilot phase in 2015-2016 along with five other countries from around the world (The UK, China, Vietnam, Ghana and Fiji).

We attempt to gain insight into the complex interplay of the changes in the physical parameters of the climate regime in Russian permafrost regions, impacts they have on the state of the frozen ground and northern environment, and socio-economic consequences of such impacts. The later include the public perception of the climatic and environmental changes and legislative decision-making on regional climate adaptation policies. We strive towards placing the multi-factual changes in Russian permafrost regions in the context of sustainable regional development. The ultimate goal of this study is to assist efforts on developing effective climate adaptation strategies and bridging the gap between the Russian and international environmental policymaking in permafrost regions.

Our study synthesizes results and key findings from the scientific papers, national and international assessment reports, including many of those published in Russian, which are not available to the western scientific community. We start with the brief overview of the observed climatic changes in Russia over the past few decades; zoom into permafrost regions and analyze the observed and projected for the future changes in the state of the frozen ground. We continue with the analysis of potentially detrimental processes associated with permafrost degradation, such as landslides, coastal erosion, thermokarst, uneven ground settlement and loss of bearing capacity, which may have destructive effect on the infrastructure and regional economy. And, lastly, we place the findings of our assessment in the context of adaptation and decision making.

Observed climatic changes in Russia and their impacts on permafrost

Russian permafrost regions demonstrated one of the highest rates of climate change in the past decades, and many of the environmental impacts predicted earlier have already been observed (Hartmann et al., 2013; Kattcov and Semenov, 2014). According to the Second climate assessment report (Kattcov and Semenov, 2014), in the past 40 years the annual-mean air temperature over the Russian territory was rising at an average rate of 0.43°C per decade, which is 2.5 times the global rate. Temperature changes were not uniform across space and through the seasons (Fig. 1). Warming was more pronounced in the Russian Arctic and subarctic, including the permafrost regions, where the mean-annual temperature was rising by 0.5-0.9 °C per decade. The European part of Russia demonstrated warming of 0.2-0.6 °C per decade with relatively small variations over seasons. In the rest of the country, the rate of warming differed by season and was the highest in the spring and in the summer (up to 1.0-1.2 °C per decade in the North of Siberia) and moderate in the fall (0.4-0.6 °C per decade with the least pronounced regional differences). Winter temperature changes had a complex regional pattern and ranged from a rise by 0.4-0.8°C per decade in Central and Northern Siberia, Yakutia and the Russian Far East, to a decline of 0.2-0.6°C per decade in southern Siberia and Chukotka.

Asymmetrical seasonal distribution of temperature changes with the most pronounced warming in spring and in the fall has direct implications in permafrost regions leading to earlier snowmelt, longer and warmer snow-free period, and, ultimately, to warming and deeper seasonal thawing of permafrost.

Annual sums of precipitation in the past four decades rose in most Russian regions at the average rate of 0.8 mm/month per decade with large interannual and regional variations (Fig. 2). Effect of precipitation on the state of permafrost is two-fold, depending on whether it is snow or rain. Snow has low thermal conductivity and insulates underlying permafrost from much colder air in winter. In the absence of snow, rain penetrates into the upper soil layer, brings extra heat, and increases soil moisture and soil thermal conductivity. In both cases the ultimate effect is warming and deeper seasonal thawing of permafrost.

Changes in the physical parameters of the atmospheric climate led to a cascade of interrelated environmental impacts in permafrost regions, which include changes in the distribution of vegetation zones, hydrology, and thermal state of the frozen ground. Further in the report we focus on permafrost changes, whereas changes of the other non-climatic environmental factors are considered only in the context of their effect on the frozen ground.

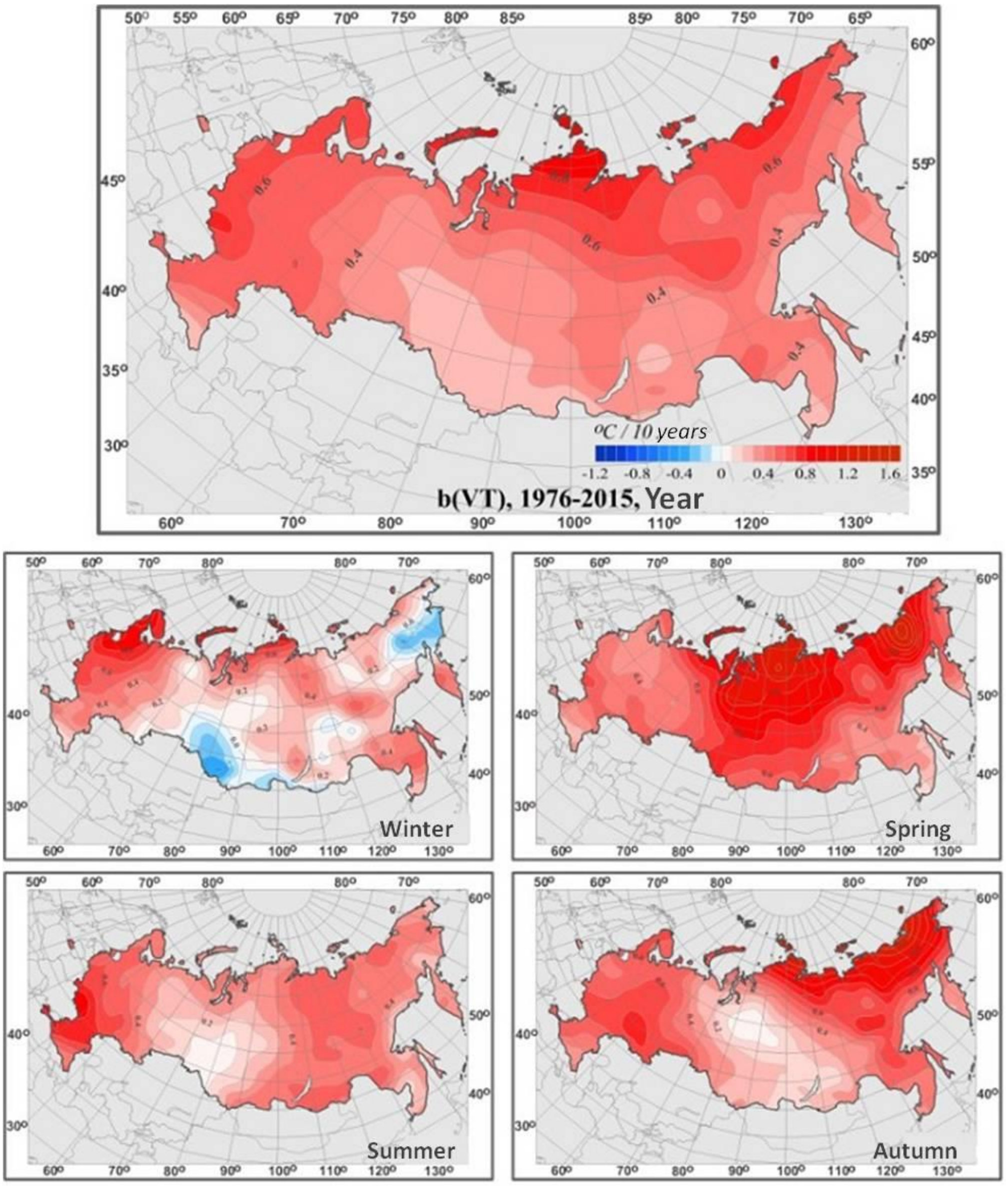


Figure 1. Air temperature trends in the period 1976-2015 (ºC/10 years) (2016)

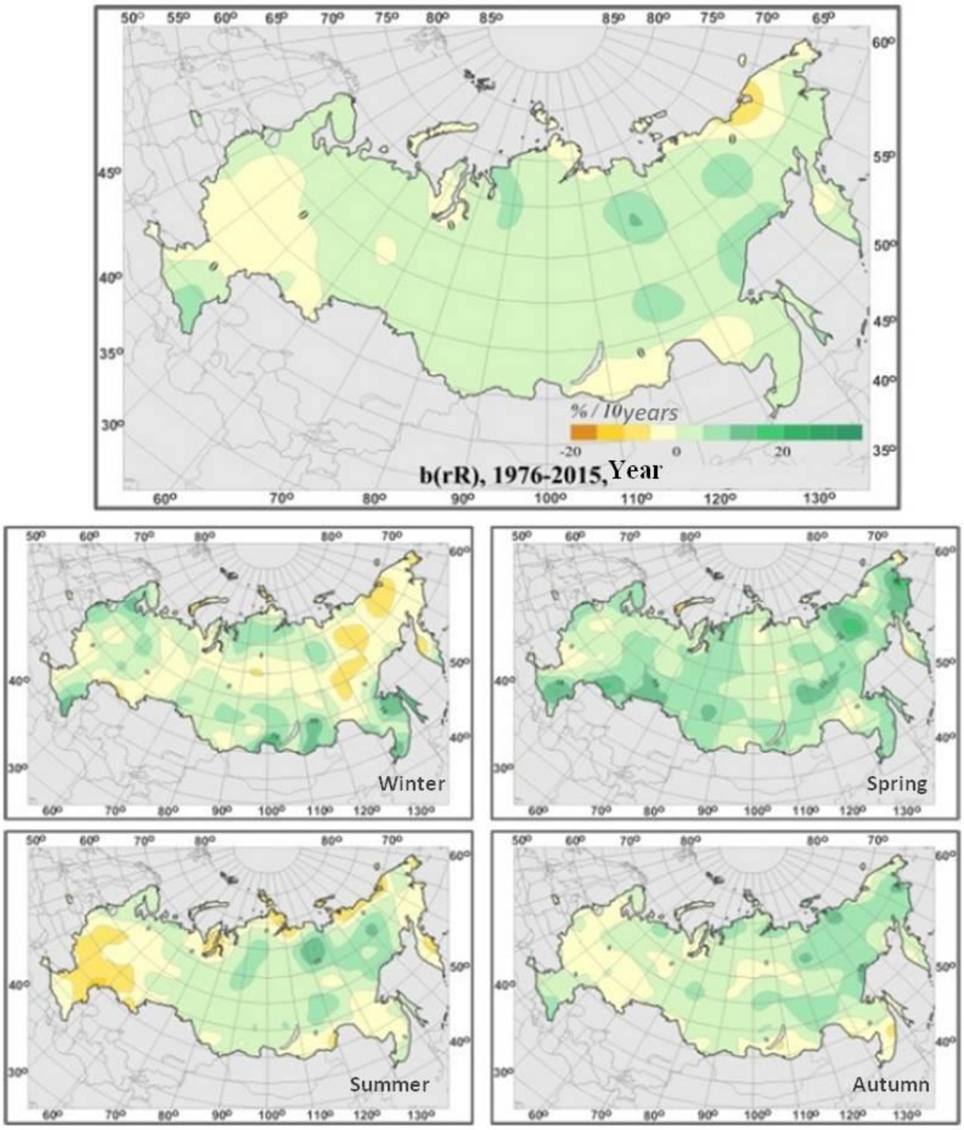


Figure 2. Precipitation trends in the period 1976-2015 (%/10 years) (2016)

The state of permafrost is best characterized by the ground temperature and active-layer thickness (ALT), i.e. the depth of the maximal propagation of the seasonal thawing. Data on permafrost temperature are available from sparse observations in boreholes (to depths up to 10-20 m, data are available at http://gtnpdatabase.org/boreholes) and from observations on meteorological stations (to depths up to 3.2 m, about 140 stations located in Russian permafrost regions, data at http://meteo.ru/data/164-soil-temperature). Annual data on ALT are available since 1990 from observational sites located in the continuous and discontinuous permafrost zones throughout Russia, data are available at https://www2.gwu.edu/~calm/. Map in figure 3 shows the location of the borehole and ALT observational sites.

Borehole data indicate that permafrost temperature has increased by 1 to 2°C in northern Russia in the past 35 years (Romanovsky et al. 2010). At colder permafrost sites in the Polar Ural, temperatures at 15 m depth increased by 0.5°C per decade since the late 1980s (Fig. 4). Less pronounced warming was observed at warm sites with permafrost temperatures few degrees below the freezing point. In the European North of Russia and in the western Siberian Arctic, temperatures at 10 m depth at cold permafrost sites have increased by ~0.4°C to 0.6°C per decade since the late 1980s with less warming observed at warm sites.

While borehole temperature data are indicative of the long-term permafrost changes, active layer thickness responds to the summer temperatures of the individual years, and are thus representative of the shorter term variations in climate. Of 64 observational sites that have been established in Russia, less than 20 have continuous records longer than 10 years. Analysis of these records indicated that while ALT trends vary by region, most of them demonstrate an increase in the last decade compared to 1990s (Fig. 5).

Even within the northernmost zone of continuous permafrost, the recent increase in ground temperatures caused permafrost thawing at selected locations. This is exemplified by the Cape Bolvansky in the European North of Russia, where thawing penetrated to the depths up to 8 m over the past 30 years (Malkova et al., 2014).

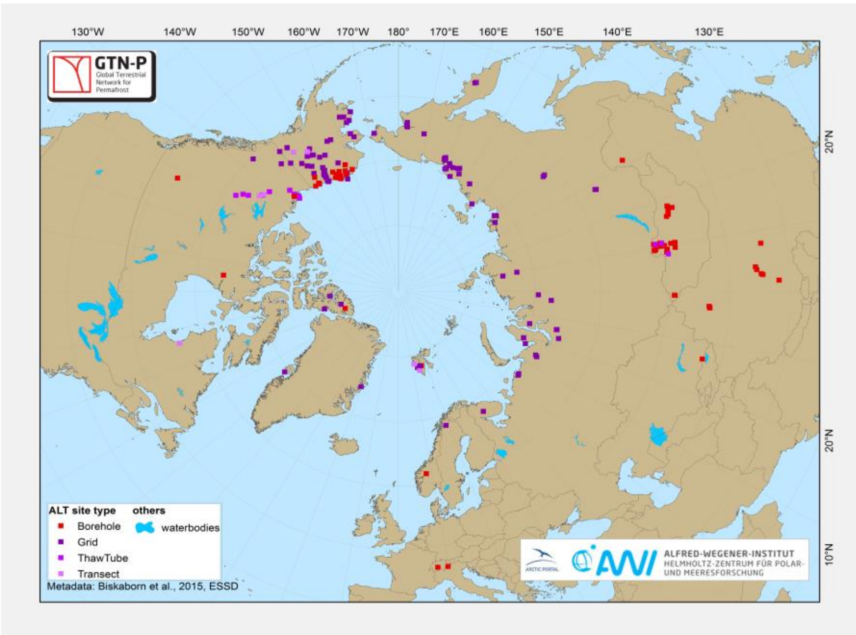


Figure 3. Location of the borehole permafrost temperature and ALT monitoring sites.

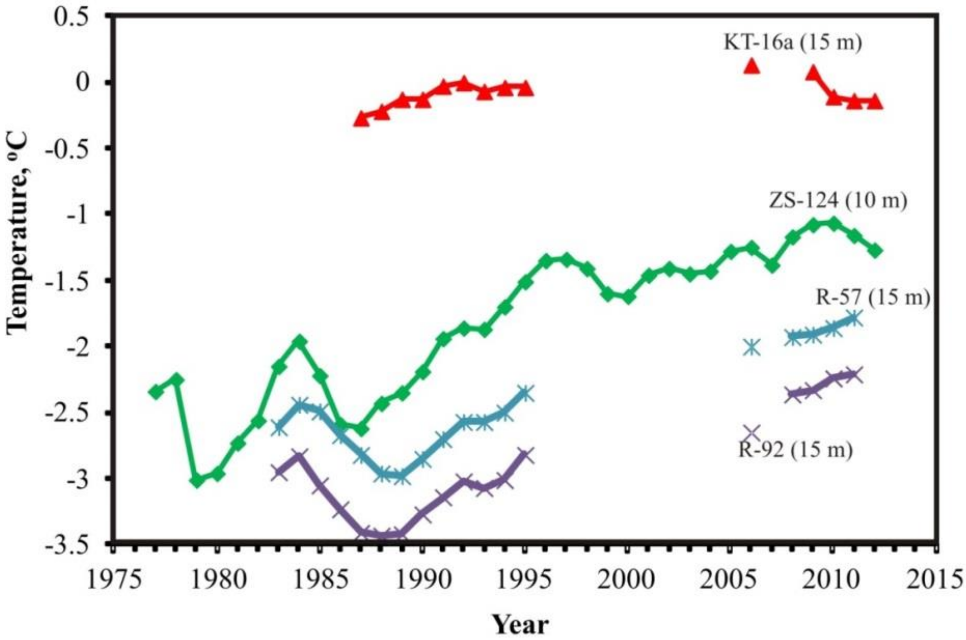


Figure 4. Changes of annual mean permafrost temperatures at 10 and 15 m depth at several research sites in the Polar Ural.

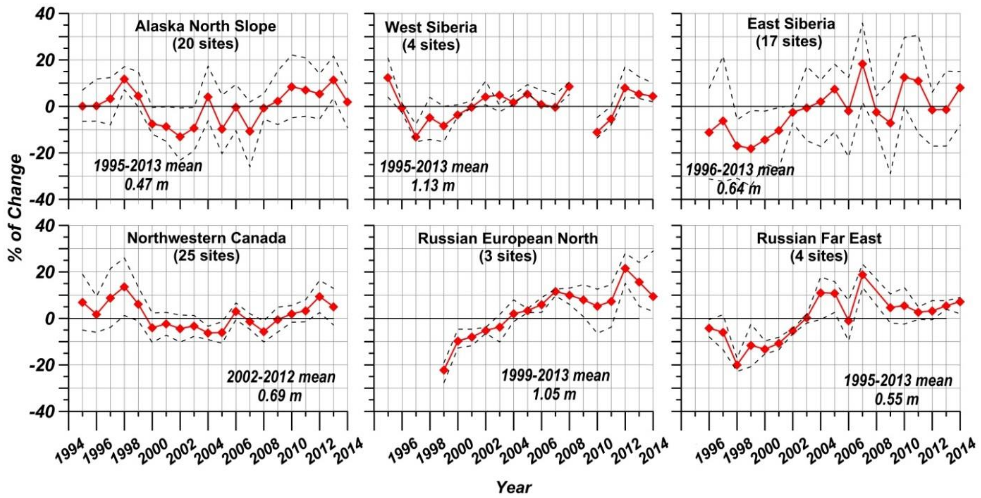


Figure 5. Changes in the active-layer thickness in Russian permafrost regions. The data are presented as annual percentage deviations from the mean value for the period of observations. Only sites with at least 10 years of continuous thaw depth observations are shown in the figure. Solid red lines show mean values. Dashed black lines represent maximum and minimum values (from Romanovsky et al. 2015).

Environmental impacts of thawing permafrost

Environmental impacts of thawing permafrost are associated with the geomorphological processes leading to changes in the landscape, massive ground movements, soil subsidence and thermokarst. Some of the most important processes are the following.

Coastal erosion

Every year about 30 km^2 of land along the Russian Arctic coast are flashed to the water due to erosion (Anisimov, 2010). The rate of coastal erosion is governed by several factors among which are the wave action, in particular storms, presence of the buried ground ice and the thermal state of the frozen ground along the coast. While the average rate of coastal erosion for the entire Arctic coast is approximately 0.5 m/y, at numerous coastal segments the rates are much higher and vary with time. As follows from the map in figure 6 (Lantuit et al., 2012), Russian Arctic coasts demonstrate generally higher rates of coastal erosion than Greenland, Canada and Alaska.

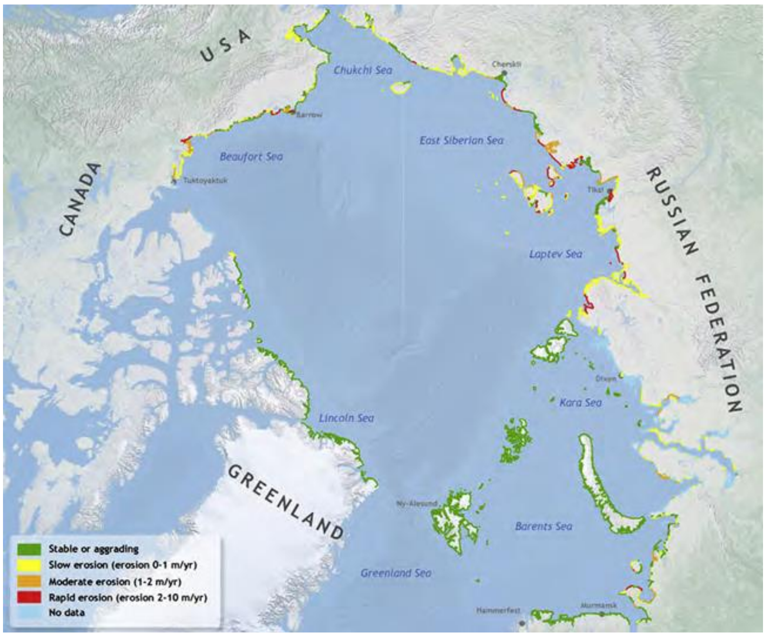


Figure 6. Circum-Arctic map of the coastal erosion rates (Lantuit et al., 2012).

In the Russian Arctic long-term monitoring of the coastal dynamics of western Yamal near the Marre-Sale Polar station during 1979-2010 indicated a long-term average rate of coastal retreat of approximately 1.7 m/y, with a maximum of 3.3 m/y (Vasiliev et al., 2011). Monitoring of the Kara Sea coasts showed that the highest rates of coastal retreat occurred during 2007-2010. Coasts retreat at an average rate of 13 m/y on Yugorsky Peninsula (Khomutov, Leibman, 2008) and up to 8 m/year at Cape Sopochnaya Karga in Yenisey Bay (Gusev, 2011). Satellite data and field monitoring for the Barents Sea indicated coastal retreat rates of up to 15 m/y, with an average rate of approximately 2.6 m/y in 2009-2012, which is more than twice higher than in the period 2002-2009 (Kizyakov et al., 2013). Such high rates are explained by a longer ice-free period in the Barents Sea than in the Kara and Laptev Seas, and associated larger wave-action effects. In the Laptev sea coastal retreat rates vary from 0.5 to 5.9 m/y, which is lower than in the

Kara and Barents Seas (Pizhankova and Dobrynina, 2010; Pizhankova, 2011). Retreat rates here are lower due to local topographic features, which restrict the development of waves. Long-term average rates of coastal erosion were estimated to be 0.7 m/y for the entire coast of the Laptev Sea and 1.0 m/y for the East-Siberian Sea.

Coastal erosion is already affecting the settlements, geodesic and navigational infrastructure, such as the fuel tanks and light houses. Particular concerns are associated with the damage and loss of isotopic thermo-electric elements that are used to power the light houses. Several such units have been flashed to the sea due to coastal erosion. Some of the detrimental impacts of coastal erosion are illustrated in figures 7 and 8 (Anisimov, 2010).

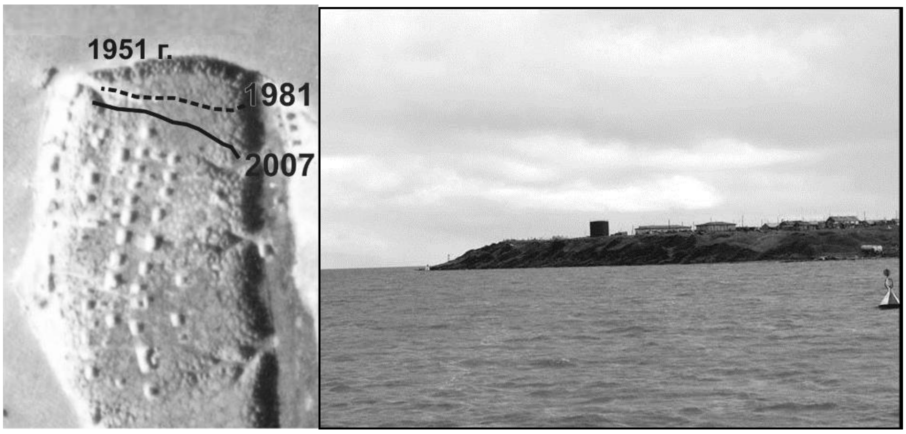


Figure 7. On the left – the gradual inland advancement of the shore-line on the Bykovskiy peninsula, Laptev sea. On the right – coastline approaching the fuel tank and residential buildings in the settlement Bykov Mys.

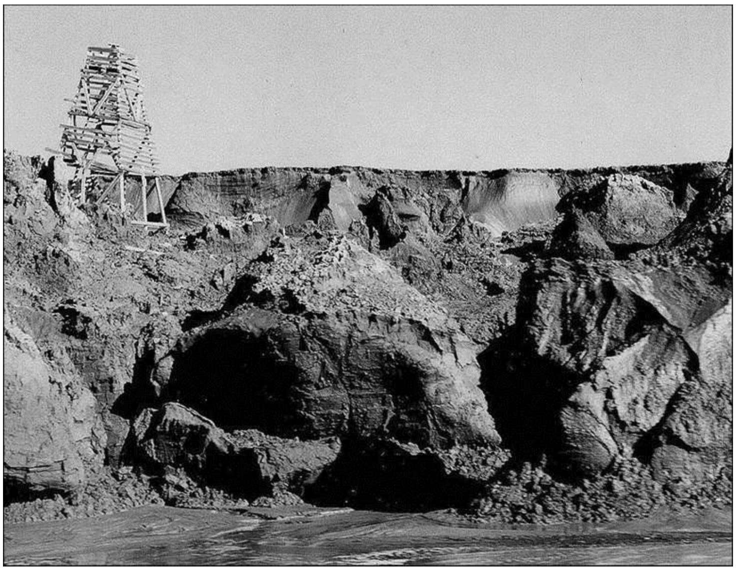


Figure 8. Navigational sign “Vankino” on Bolshoi Ljakhovskoi island in the East-Siberian Sea been affected by coastal erosion and further destroyed.

Besides climatic, permafrost, and sea ice changes, coastal erosion is governed by anthropogenic and technogenic factors (Streletskiy et al., 2014). This is exemplified by construction of oil terminals in Varandei (Yamal peninsula). Industrial activity around Varandei Oil Field (Pechora Sea coast) has already resulted in twice the rate of coastal retreat compared to a natural environment (Ogorodov, 2005). One of the major factors that played a role in increasing the rate of erosion was the excavation and removal of shoreline sediment for construction, which combined with vegetation degradation, led to increased ALT. Deeper thaw made sand dunes more susceptible to wind deflation and erosion.

Landslides

These thaw-related features are mainly observed in the continuous permafrost zone today, where massive ground ice actively accumulated in the permafrost history and never thawed (Fig. 9). The activation of landslides is controlled by increasing atmospheric precipitation and by changes in summer air temperature. The future occurrence of active-layer detachments should probably move northward, where conditions for ice formation at the active-layer base are still preserved. The northern limits of the occurrence of retrogressive thaw slumps is probably also shifting northward due to active-layer thickening towards the deep-seated massive ice bodies (Leibman et al., 2014a).

Figure 9. Landslides in the Central Yamal Peninsula. (a) and (b) Examples of typical cryogenic landslides and thermocirques of the Central Yamal Peninsula. (c) Yamal Peninsula and location of the key site of landslide research at Vaskiny Dachi. (d) Satellite image of highly dissected landscapes caused by cryogenic landslides that are typical of this region.

Thermokarst

Thermokarst is associated with thawing of ice-rich permafrost or melting of massive ground ice. It leads to ground subsidence. Accumulation of water in depressions formed by subsidence often results in the formation of a small trough pond which may evolve into a lake over time (Fig. 10). Depending on the amount of ground ice and depth of thaw beneath the lake, its depth can range from 1-3 m to 10-20 or more meters. Thermokarst lake dynamics is an indicator of climate change in the Arctic. Satellite data indicate that such processes are currently taking place in Russian permafrost regions (Biskaborn et al., 2013; Bryksina and Kirpotin, 2012;

Kravtsova and Tarasenko, 2011; Manasypov et al., 2014). Increases and decreases in lake area as a response to climate change are of a regional character (Kravtsova and Bystrova, 2009) and are linked to environmental and local climate controls. In general, there is an increase in the number and area of thermokarst lakes in continuous permafrost zone and a reduction in the number and area of lakes in discontinuous and sporadic permafrost zones.

Figure 10. . Thermokarst lakes (a), water-filled ponds at their initial stage (b), overgrowing of draining lake margins (c), Yamal. (photos by M.O.Leibman)

The modelling study (Аржанов et al., 2010) suggests that permafrost thawing in the 21st century will lead to ground subsidence between 0.4 and 1.0 m, with large regional variations (Fig. 11).

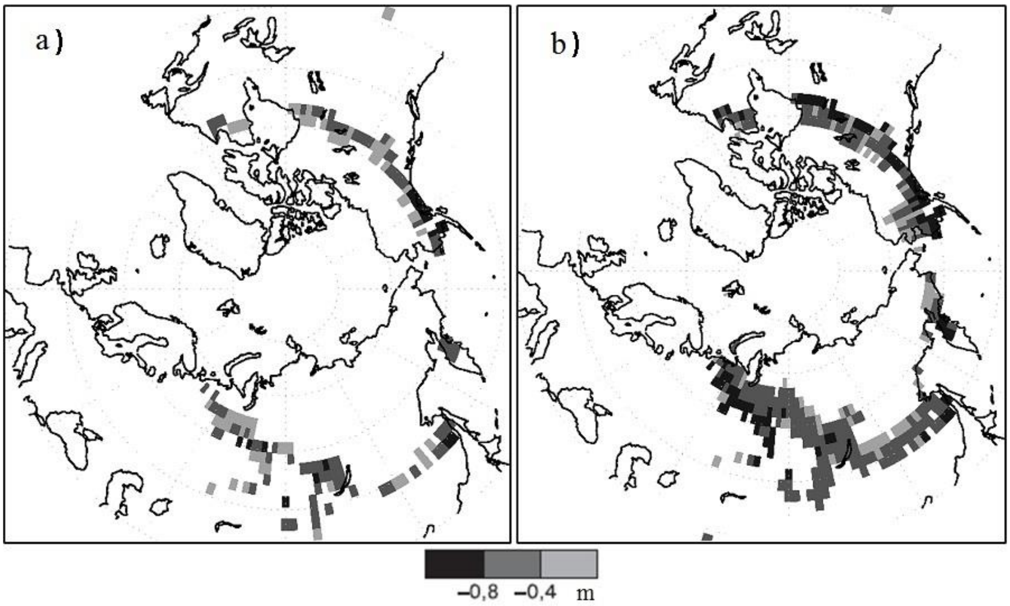


Figure 11. Projected ground subsidence due to thawing permafrost by 2050 (a) and by 2100 (b).

Economic impacts of thawing permafrost

There is increasing evidence that the ongoing climatic changes have already exceeded the level of natural variability accounted for in construction and management practices and norms regulating many types of human activities. Changing climatic conditions may benefit some aspects of arctic economies as heating costs are likely to decrease, and diminishing sea-ice extent has the potential to foster economic development along the coasts. However, these benefits may be outnumbered by the new challenges as coastal erosion is expected to intensify due to increasing wave activity, shorter winter road operational seasons lower the accessibility of remote settlements, and thawing permafrost may not be able to support existing infrastructure.

In the absence of a well-developed network of all-season roads, winter ice roads are particularly important in permafrost regions to keep connections with the mainland. This is the case not only with small remote settlements, but also with large cities like Yakutsk. The capital of Sakha Republic with a population of 300 thousand is located on the left bank of the Lena river, while the main tracks of the Siberian rail network connecting the region with the rest of the country and providing essential year-round supplies are located ca 400 km southward on the opposite river bank. Until now, there was no bridge over the Lena river, and heavy trucks carry supplies to the city using either the ice road or ferries, as illustrated by the top two photos in fig. 12. The lower two photos illustrate the seasonal differences in the transportation conditions in the absence of the permanent all-season roads. The duration of the ice period on rivers in the circumpolar North has been decreasing since the 1970s on average by 12 days/100 years with up to 4 times greater rates in the high Arctic. Statistically, an increase in autumn and/or spring air temperature of 2 to 3°C leads to a 10- to 15-day shift in freeze-up and/or break-up of the river ice in the Arctic (AMAP 2011).

Figure 12. Seasonal differences in the transportation conditions in permafrost regions in the absence of permanent all-season roads. Upper photos – crossing of the Lena river in the vicinity of Yakutsk in winter and in summer. Lower photos – winter and summer roads in Yakutia.

The duration of the winter road operational period depends on winter temperature and snow fall, which have changed significantly and unevenly in the Russian North since the 1960s. The study (Anisimov and Streletskiy, 2015) indicates that in the past 30 years changes have already occurred (Fig. 13). While in Yakutia and selected regions in Central Siberia the operational period of the winter roads has increased on average by several days, in most industrialized areas of West Siberia, including the oil and gas extracting provinces on Yamal, it has dropped by more than 10 days. Other economically vital regions with a decrease in potential accessibility include heavily industrialized areas around Noyabrsk, Noviy Urengoy, and Nadym; regions along the Yenesey River north of Igarka up to Dickson; around Chersky in Northeastern Yakutia; and Pevek and Anadyr in Chukchi AO. Other Arctic nations are facing similar problems. According to (Stephenson et al., 2011), by the mid-21st century the accessibility of remote settlements currently served by winter roads will fall on average by 13 percent, and the area, where winter road operations remain economically feasible, will reduce by 1 million km^2. However, unlike the case with Alaska and Northern Canada, Russia does not have a developed network of local airlines effectively serving routes in the High North.

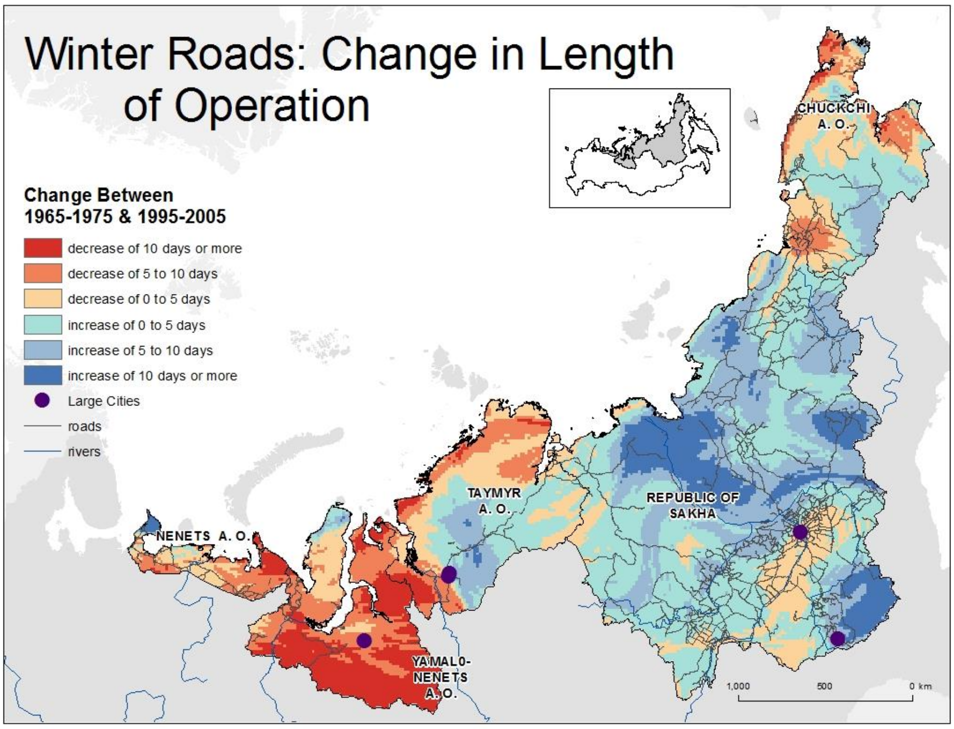


Figure 13. Changes in the duration of the winter road operational period between 1970s and 2000s. (Anisimov and Streletskiy, 2015).

Social consequences

The social consequences of the changes in the duration of the winter road operational period could be evaluated by the number settlements and people in the affected regions. Such data were collected and analyzed by Hatleberg (2012), the data are presented in Tables 1 and 2. Of the total settlements, 47% experienced some degree of decrease in days of winter road operability. However, these settlements accounted for 987,600 people, or 74% of the total population of Russian permafrost regions. Conversely, 53% of the total settlements experienced some degree of increase, with 339,800 people, or 25% of the total, living there. The mean number of days winter road could operate for settlements across the study area remained constant at 222 days between the two time periods. The minimum amount of operable days was 176 during the 1970 time period and in the 2000 time period. The maximum was 250 operable days in both periods.

The largest decreases in potential length of winter road operability occurred in northern Chuckchi AO, southern Yamalo-Nenets AO, and eastern Nenets AO where some settlements saw winter road operability decrease by 4%, equating to decreases between 10 and 15 days from the 1970 time period to the 2000 time period. Ten settlements were affected to this extent, affecting 264,600 people. These included: Cape Schmidt, Anadyr, and Mining in the Chuckchi AO; Naryan-Mar and Amderma in Nenets AO; and Muravlenko, Noyabrsk, Novyi Urengoy, and Taz in Yamalo-Nenets AO. For these cities the decreased operability season in 2000 ranged from: 223 to 235 days in Chuckchi AO; 209 to 215 days in Nenets AO; and 202 to 226 days in Yamalo-Nenets AO.

Yakutia is the only region in which settlements have witnessed an increase in winter road operability between the 1970 and 2000 time period, equating to between 10 and 11 days, affecting 11,400 people. These settlements include: Batagay, Deputy, and White Mountain. For these cities, the increased operability of the season in 2000 ranged from 241 to 244 days. In fact, all but two of the 53 settlements experiencing colder temperatures, and therefore increased winter road operability, occurred in Yakutia. The remaining two settlements were in Chuckchi AO.

Table 1. Distribution of urban settlements by change in winter road season

Percent Change	Chuckchi AO	Nenets AO	Taymyr AO	Yakutia	Yamalo-Nenets AO	Study Area
< -4%	4	2	0	0	4	10
-2 - -4%	6	1	3	4	9	23
0 - -2%	1	0	2	11	0	14
no change	1	0	0	1	0	2
0 - 2%	1	0	0	30	0	31
2 - 4%	1	0	0	18	0	19
> 4%	0	0	0	3	0	3
TOTAL	14	3	5	67	13	102

Table 2. Distribution of present population for urban settlements by change in winter road season

Percent Change	Chuckchi AO	Nenets AO	Taymyr AO	Yakutia	Yamalo-Nenets AO	Study Area
< -4%	15,900	20,200	0	0	228,500	264,600
-2 - -4%	23,600	7,000	189,800	36,100	158,100	414,600
0 - -2%	400	0	62,600	245,400	0	308,400
no change	400	0	0	7,700	0	8,100
0 - 2%	3,200	0	0	279,100	0	282,300
2 - 4%	2,600	0	0	43,500	0	46,100
> 4%	0	0	0	11,400	0	11,400
TOTAL	46,100	27,200	252,400	623,200	386,600	1,335,500

As mentioned above, the biggest cities with the largest decreases are Noyabrsk and Novyi Urengoy, both decreasing between 4 and 5%, ending with a winter road season average of 202 and 219 days respectively in the 2000 time period. Norilsk in the Taymyr AO decreased by five days, or 2%, down to 240 days in 2000.

Though slightly more settlements experienced increases in the number of days winter roads could operate, significantly more of the population experienced a decrease. Of the settlements experiencing the most change, decreases in winter road operability affected more settlements and people than those that benefited from an increase in accessibility. However, it is important to note here that winter road accessibility will affect and influence greater populations than simply those people that inhabit a specific location.

Particular concerns are associated with the fate of the structures built upon the frozen ground. Linear structures, such as roads, rail roads and pipelines, are particularly vulnerable to thermokarst and differential ground subsidence (fig. 14). Russia has an extensive network of pipelines with a total length of about 350,000 kilometers, of which more than 71,000 kilometers traverse permafrost regions. Thawing permafrost leads to the deformation and damage of pipelines, exacerbates the problems of pipeline maintenance, and increases operational costs. According to the survey conducted by the Earth Cryosphere Institute in Tumen, 23% of the total number of accidents in the geotechnical systems serving the needs of the extracting and transportation industries are attributed to changes of permafrost. As a result, the gross industrial production is reduced by 29%. About 55 billion rubles are spent annually to fix the mechanical deformations resulting from uneven settlement of the thawing permafrost (Anisimov, 2010).

Figure 14. Roads and railroads affected by uneven ground subsidence due to thawing permafrost.

Buildings in permafrost regions are based on piles anchored in the frozen ground. The bearing capacity of pile foundations decreases with the rising ground temperature. Climatic warming led to a decrease in the permafrost bearing capacity on average by 17% and at selected locations up to 45% since 1970s. Thawing permafrost caused deformation and damage to numerous buildings in northern cities. Most of these structures were built in the 1960s and 1970s, and the effect of climate change had not been incorporated into their design. A survey of structures conducted in selected cities in the Russian Arctic in the early 2000s indicated that a significant number of structures were already affected by deformations due to thawing permafrost, i.e. about 10 percent of buildings in Norilsk, 22 percent in Tiksi, 55 percent in

Dudinka, 35 percent in Dikson, 50 percent in Pevek and Amderma, 60 percent in Chita, and 80 percent in Vorkuta.

Streletskiy et al., 2012 has provided a methodology for geographic assessments of changes in engineering properties of frozen ground due to observed climatic change. Average bearing capacity for 1960-1970 was chosen as a reference point representing 100%. This decade represents unprecedented development of the Russian Arctic and associated urban infrastructure which is still in use. The range of decadal changes in bearing capacity attributable to climatic changes is presented in Table 3.

Table 3. Decadal changes in foundations bearing capacity due to observed climate change

Region	Settlement	Bearing capacity of foundations, %				
		1960th	1970th	1980th	1990th	2000th
West Siberia	Salekhard	100	91-103	72-86	81-82	68-70
	Nadym	100	96-101	77-91	78-100	64-95
	Noviy Urengoy	NA	NA	100	97-116	91-96
	Noviy Port	100	105-114	86-93	87-92	63-76
Central Siberia	Norilsk	100	102-105	88-93	84-92	85-94
	Dudinka	100	103-110	93-94	90-94	74-82
East Siberia	Yakutsk	100	91-98	80-92	59-84	54-80
	Bilibino	NA	100	90-98	97-100	80-91
	Tiksi	100	99-100	96-98	95-97	93-96
	Anadyr	100	101-104	92-100	75-94	52-84
	Chersky	100	100-101	97-98	96	76-84

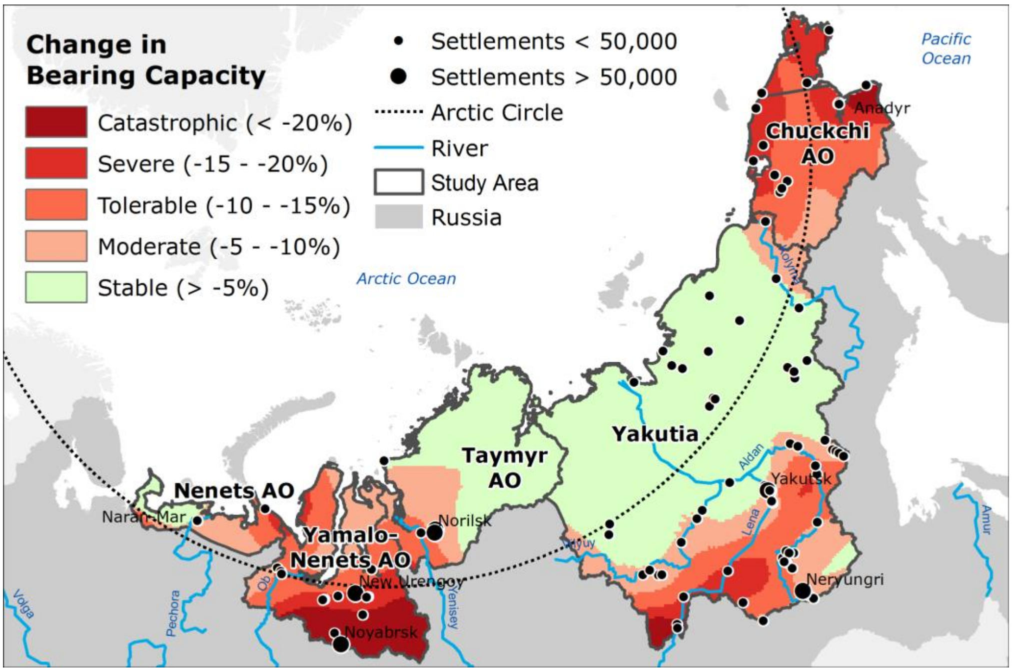


Figure 15. Changes in permafrost bearing capacity between the 1970s and 2000s.

The analysis described above was conducted to evaluate the spatial distribution of changes in bearing capacity in Russian permafrost regions. Three time periods were used to evaluate climate-induced bearing capacity changes: decadal differences from 1970 to 2000, 1970 to 2020, and 1970 to 2050. These time periods represent conditions faced by infrastructure built during the Soviet construction boom of the 1960s and 1970s. Figure 14 shows the bearing capacity changes from the reference 1970 period expressed in percentages for the three periods. The analysis indicates significant reduction in the ability of the frozen ground to support structures throughout the Russian permafrost regions with the most pronounced changes expected at the southern fringes of the permafrost.

The mean percent change in bearing capacity between the 1970 and 2000 time periods across the Russian permafrost regions has decreased slightly, by 7%. However, if change is assessed in specific settlements, where many of the buildings and infrastructure are actually located, the decrease is larger at 9.6%. The map in Figure 15 indicates that the greatest decreases in bearing capacity occurred in southern Yamalo-Nenets AO and north and east Chuckchi AO, along with southwestern Yakutia, where decreases in bearing capacity reached catastrophic or severe levels. These regions had the warmest MAAT in the 2000 time period and also had temperature increases of more than 1ºC between the two time periods. Decreases in bearing capacity also occurred to a lesser extent in eastern Nenets AO, northern Yamalo-Nenets AO, far western Taymyr AO, southeast Yakutia, and western Chuckchi AO, where decreases ranged from moderate to severe. These areas had colder temperatures but had warmed considerably between the time periods. Northern Yakutia, as with eastern Taymyr AO and most of western Nenets AO, remained stable with a decrease less than 5%. This is because these areas had cooler MAATs in the 2000 time period than in the 1970 time period and also generally colder areas (with the exception of Nenets AO).

Table 4 shows the distribution of settlements impacted by varying percentages of bearing capacity between the 1970 and 2000 time periods, while Table 5 shows the affected population of these settlements. The moderate category, defined as decreases between 5% and 10%, contained the most settlements, 33 settlements, and the largest population, at 653,100 people. Combined, the most troubling categories, catastrophic and severe, accounted for 28 settlements and 375,400 people. The stable classification accounted for 22 settlements, which accounted for the smallest amount of people, 90,300.

The largest decreases in bearing capacity of more than 20% occurred in eastern Chuckchi AO along the Pacific Ocean, southern Yamalo-Nenets AO, and southeastern Yakutia. This is because these areas had temperature increases of more than 1ºC between the two time periods, along with having the warmest annual-mean air temperatures in the 2000 time period. Seven settlements were affected to this extent, affecting 166,000 people. These settlements included: Noyabrsk, Muravlenko, and Tarko-Sale in Yamalo-Nenets AO; Bering and Providence in Chuckchi AO; and Vitim and Peleduy in Yakutia.

Of these areas, the most concerning are the three settlements in the Yamalo-Nenets AO, which together accounted for a population of 151,500. Here, in Noyabrsk, which had one of the highest decreases in the range at 26.7%, 96,600 people were potentially affected. The second most concerning area was nearby Muravlenko, with a similar decrease of 26.2%, affecting 36,300 people. This is also concerning as considerable natural gas and oil infrastructure exists throughout southern Yamalo-Nenets AO.

Areas least affected were 22 settlements considered stable, with percent changes of less than 5%. All except one, Dixon in Taymyr AO, were located in northern or central Yakutia. Of the four settlements that experienced increases in bearing capacity, all were located in northern Yakutia. Northern, White Mountain, Deputy, and Ust-Kuyga all had a small increase in bearing capacity between the two time periods. In these areas, bearing capacity increased; it is of note that these settlements are also located where air temperatures decreased between the time periods.

As mentioned above, the biggest cities with the largest decreases are Noyabrsk, decreasing 27.6%, and Novyi Urengoy. Novyi Urengoy had a severe decrease in bearing capacity, decreasing 15.3%. Norilsk, Neryungri, and Yakutsk all experienced moderate changes, decreasing 9.6, 9.2, and 5.8%.

Table 4. Distribution of urban settlements by change in bearing capacity

Percent Change	Chuckchi AO	Nenets AO	Taymyr AO	Yakutia	Yamalo-Nenets AO	Study Area
Catastrophic (<-20%)	2	0	0	2	3	7
Severe (-15 - -20%)	9	1	0	2	6	18
Tolerable (-10 - -15%)	3	0	2	13	4	22
Moderate (5 - 10%)	0	2	2	29	0	33
Stable (> -5%)	0	0	1	21	0	22
TOTAL	14	3	5	67	13	102

Table 5. Distribution of present population for urban settlements by change in bearing capacity

Percent Change	Chuckchi AO	Nenets AO	Taymyr AO	Yakutia	Yamalo-Nenets AO	Study Area
Catastrophic (<-20%)	5,200	0	0	9,300	151,500	166,000
Severe (-15 - -20%)	32,600	1,800	0	10,300	164,700	209,400
Tolerable (-10 - -15%)	8,300	0	51,800	86,200	70,400	216,700
Moderate (5 - 10%)	0	25,400	199,500	428,200	0	653,100
Stable (> -5%)	0	0	1,100	89,200	0	90,300
TOTAL	46,100	27,200	252,400	623,200	386,600	1,335,500

Streletskiy (2015) presented the model-based projection of the permafrost bearing capacity under the changing climatic conditions for the first quarter and mid-21st century (Figure 16). Results suggest that by mid-21st century bearing capacity will decrease by 50%-95% in the southernmost permafrost zone and by 25%-50% elsewhere in Russian permafrost regions.

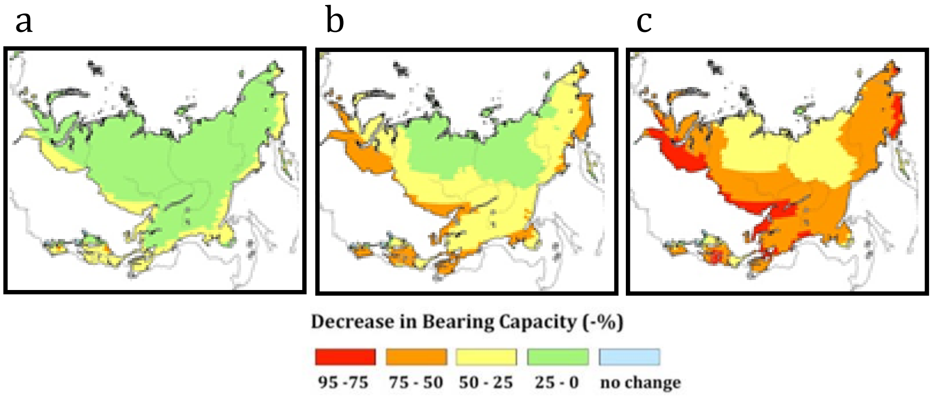


Figure 16. Mean changes in bearing capacity of the frozen ground for the Russian permafrost region. Changes are expressed in percentages from the 1965-1975 reference period for decades of 1995-2005 (a), 2015-2025 (b) and 2045-2055 (c). The average of six CMIP5 GCM models, which most closely reproduce the historical observational air temperature record for the Russian Arctic region (Anisimov & Kokorev 2013) were used to provide climatic forcing.

Energy Consumption for Heating

Energy consumption due to heating needs is an important factor in assessing living conditions across the Russian Arctic, where temperatures are extremely cold. Here the number of heating degree-days (NHDDs) is estimated by identifying the number of days in which the mean daily temperature continuously falls below 8ºC. Despite warming temperatures, the amount of days requiring heating has remained high throughout the region, with small variation in most places (Fig. 17). The mean percent change in NHDDs between the 1970 and 2000 time periods across the permafrost regions have decreased only slightly by 0.6%.

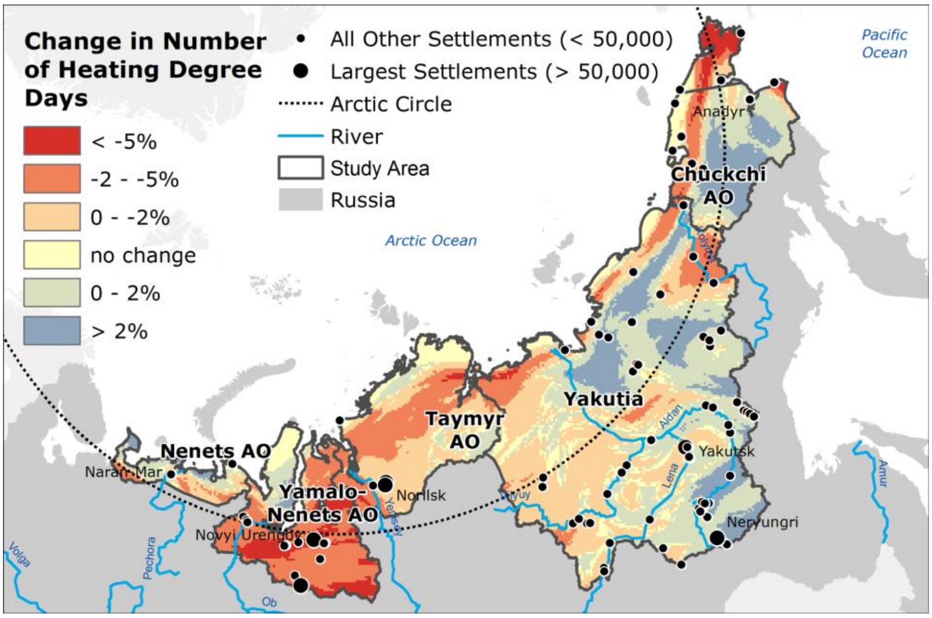


Figure 17. Percent change of the number of heating degree-days between the 1970 and 2000 time periods.

Table 6 shows the distribution of settlements likely impacted by varying percents of change in days requiring heating between the 1970 and 2000 time periods, while Table 7 shows the affected population of these settlements. Percent change in NHDDs was variable, with both increases and decreases in heating needs while other places show decreases. Along the Arctic Ocean, no change signifies places where heating was required every day of the year.

Absolute values associated with the categories of percent change of settlements of the study area are as follows: a decrease of percent change of more than 5% equated to a decrease between 15 and 29 days; a decrease of 2 to 5% equated to a decrease between 8 and 13 days; a decrease of 0 to 2% equated to a decrease of 1 to 6 days; no change indicates the same number of days in each time period; an increase of 0.1 to 2% equates to an increase of 1 to 6 days; and an increase of more than 2% indicates an increase of 6 to 8 days.

Of the total, 48 settlements, slightly less than half, experienced some degree of decrease in days requiring heating due to warmer temperatures, accounting for 995,900 people. On the other hand, 44 settlements of the total experienced some degree of increased in heating days signifying colder temperatures, accounting for 276,400 people. Slightly fewer settlements experienced extended heating seasons, though three and a half times as many people across the study area experienced a decrease in heating days compared to those with an increase. Considering categories of highest percent change make these differences even more pronounced.

Table 6. Distribution of urban settlements by change in number of heating degree-days

Percent Change	Chuckchi AO	Nenets AO	Taymyr AO	Yakutia	Yamalo-Nenets AO	Study Area
< -5%	2	0	0	0	6	8
-2 - -5%	1	0	0	2	7	10
0 - -2%	2	2	4	22	0	30
no change	4	1	1	4	0	10
0 - 2%	5	0	0	30	0	35
> 2%	0	0	0	9	0	9
TOTAL	14	3	5	67	13	102

Table 7. Distribution of present population for urban settlements by change in number of heating degree-days

Percent Change	Chuckchi AO	Nenets AO	Taymyr AO	Yakutia	Yamalo-Nenets AO	Study Area
< -5%	5,200	0	0	0	164,700	169,900
-2 - -5%	500	0	0	8,700	221,900	231,100
0 - -2%	3,600	25,400	251,300	314,600	0	594,900
no change	9,900	1,800	1,100	50,400	0	63,200
0 - 2%	26,900	0	0	219,200	0	246,100
> 2%	0	0	0	30,300	0	30,300
TOTAL	46,100	27,200	252,400	623,200	386,600	1,335,500

In the 18 settlements showing decreases in heating days above 2%, 401,000 people were affected while only nine settlements, affecting 30,300 people experienced a decrease of more than 2%. Therefore, nine more settlements and 370,700 more people experienced a decrease in heating season greater than 2% as compared to settlements and people that experienced the opposite.

The largest decreases in potential days requiring heating occurred in eastern Chuckchi AO along the Pacific coast and in central Yamalo-Nenets AO where some settlements saw heating days decrease by 5% or more, equating to decreases between 15 and 29 days between the two time periods. Eight settlements and 169,900 people were affected to this extent. These included: Providence and Bering in Chuckchi AO; Nadym, Old Nadym, Pangody, Novyi Urengoy, and Korotchayevo in Yamalo-Nenets AO. For these cities the decrease in heating days in 2000 ranged from 322 to 302 days in Chuckchi AO and 283 to 284 days in Yamalo-Nenets AO.

Other decreases between 2 and 5% occurred across Yamalo-Nenets AO, in northwestern Chuckchi AO and northeastern Yakutia, with decreases between 8 and 13 days. In Noyabrsk, Taz, Labytnangi, Tarko-Sale, Salekhard, Harp and Muravlenko across Yamalo-Nenets AO; Baraniha in northwestern Chuckchi AO; and Srednekolymsk and Zyrianka in northeastern Yakutia decreases in heating days in 2000 ranged from 270 to 334 days.

Only in Yakutia did settlements experience an increase of more than 2% of days requiring heating between the 1970 and 2000 time period, affecting nine settlements and 30,300 people. These settlements include: Upland, Zolotinka, Tommot, Silver Forest, Yllymah, Berkakit, and Chagda in the south Yakutia between Yakutsk and Neryungri; and Ust-Kuyga and Artyk in the north. For these settlements, the increase in days likely to require heating ranged from 268 to 311 days. Actually, only five of the total 44 settlements that experienced an increase in heating days across the study area where not in Yakutia. These five settlements were all located in Chuckchi AO.

Of the 10 settlements that exhibited no change between periods, six along the Arctic Ocean likely required heating all year round, requiring 365 days of heating in both time periods.

These settlements included: Amderma in Nenets AO; Dixon in Taymyr AO; and Pevek, Leningrad, Komsomol, and Cape Schmidt in Chuckchi AO. The remaining four had a range from 259 to 282 days requiring heating. All were located in Yakutia below the Arctic Circle.

Of the largest cities, the largest decrease in heating days occurred in Novyi Urengoy, which decreased 15 days, or 5%, down to 284 days in the 2000 time period. The second largest decrease occurred in Noyabrsk with a decrease of 13 days, or 4.6%, down to 270 days in the 2000 time period. Yakutsk had a decrease of two days, or 0.8%, down to 260 days in the 2000 time period. Norilsk had a decrease of two days, or 0.6%, down to 310 days in the 2000 time period. Neryungri was the only large settlement of the five to increase between the time periods. It increased four days, or 1.5%, up to 278 days in the 2000 time period.

Projected changes in Russian permafrost regions

Climate models predict that in the 21st century permafrost regions will continue warming at higher rate than most other regions (Fig. 18).

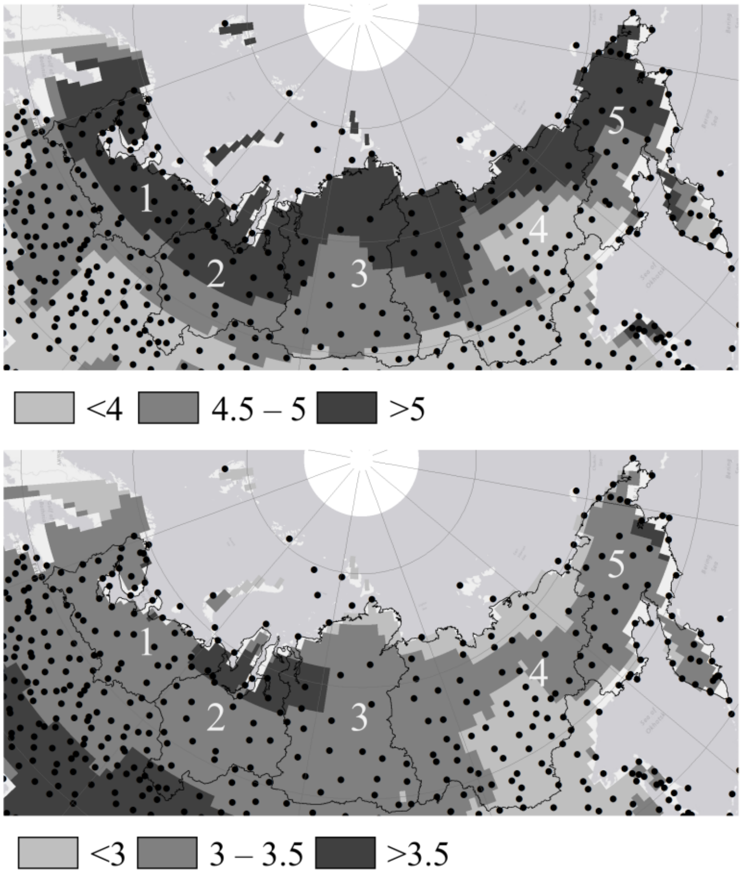


Figure 18. Mid-21st century projections of the winter (upper panel) and summer (lower panel) temperatures.

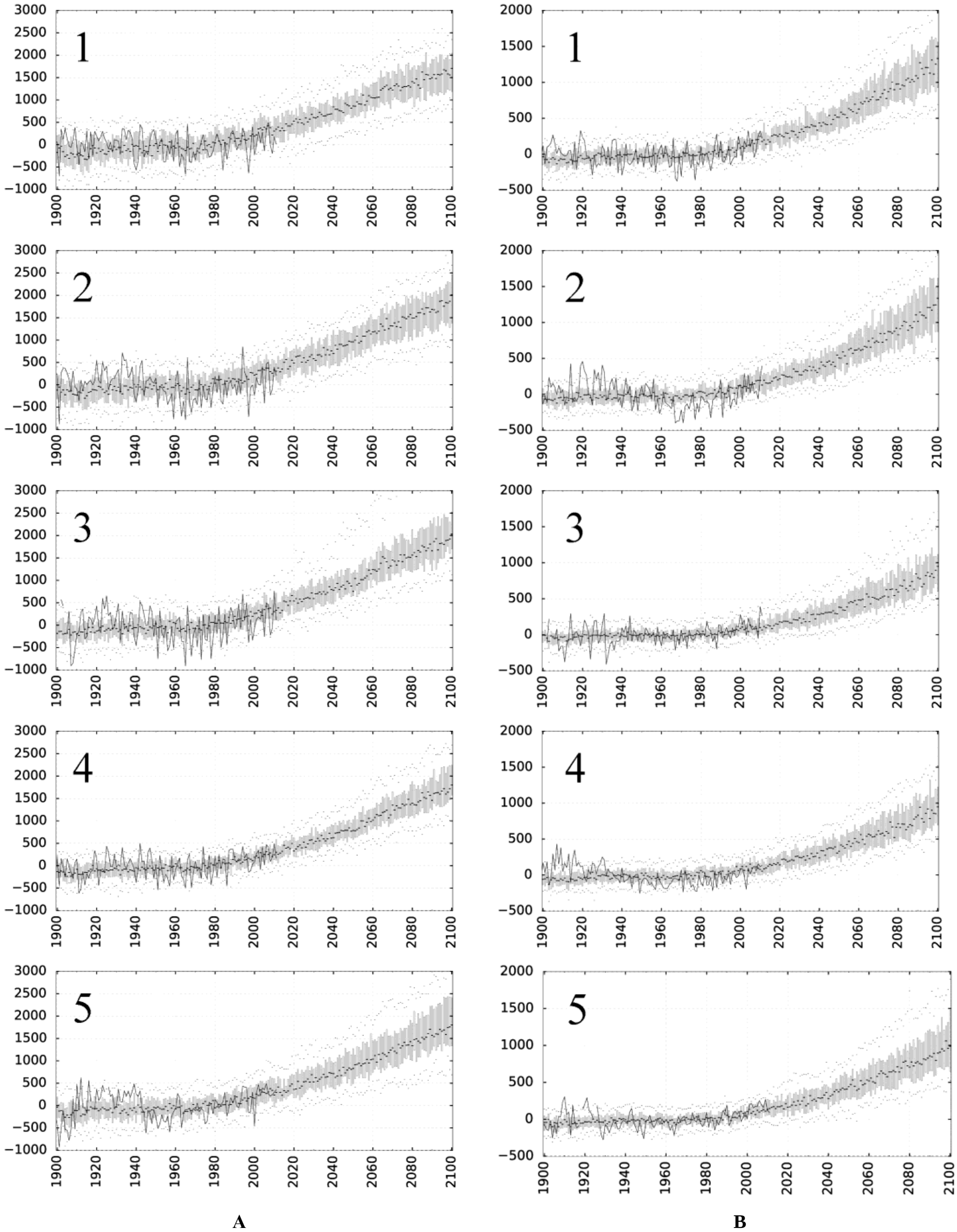


Figure 19. Historical and projected changes (departures from the 1961-1990 mean) in the accumulated degree-days of freezing (in winter, panel A) and degree-days of thawing (in summer, panel B) for 5 regions in the Russian Arctic: 1 – European North; 2 – West Siberia; 3 – East Siberia; 4 – Yakutia; 5 - Chukotka.

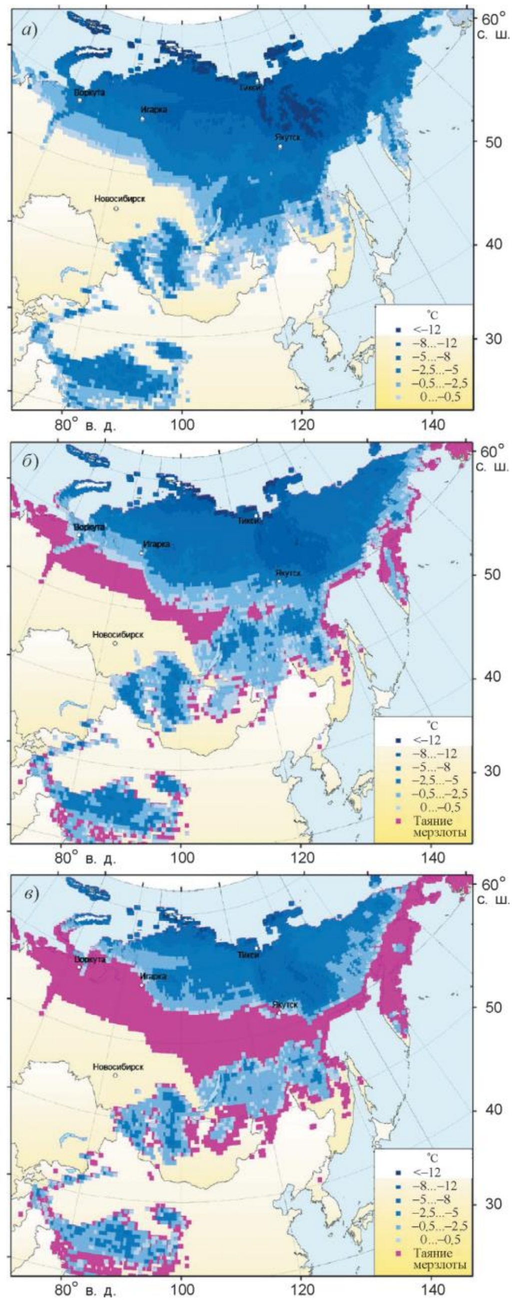


Figure 20. Current (1990-2000 period, upper map) and projected for the mid-21st century (2040-2050 period, map in the middle) and end-21st century (2090-2100 period, lower map) annual-mean temperature in the near-surface permafrost layer. Magenta color highlights regions, where permafrost is projected to disappear in the near-surface layer.

Figure 19 illustrates the historical and projected changes in the accumulated degree-days of freezing (DDF) and thawing (DDT) for 5 regions in the Russian Arctic: 1 – European North; 2 – West Siberia; 3 – East Siberia; 4 – Yakutia; 5 – Chukotka (Anisimov and Kokorev, 2016b). According to the data presented in (Anisimov and Kokorev, 2016a), accumulated winter temperature degree-days of freezing is expected to rise up to 15 percent under projected mid-21st century climate conditions, whereas the duration of the period when heating in the northern cities is needed will decline by up to one month. The rate at which the demand for heating energy is decreasing in the Russian Arctic varies from –21.8 degree-days per year (°C d/y) in North-European Russia to –27°C d/y in West Siberia and –30.2 to 31.7 d/y in Yakutia and Central Siberia due to the cumulative effect of less severe winters and the shortening of the heating period.

The expected rate of the summer warmth rise (DDT trend) decreases from west to east in the Russian Arctic, varying between 16.5 °C d/y in North-European Russia and 15.7°C d/y in West Siberia, to 11–12°C d/y in the Central Siberia, Yakutia, and Chukotka. By 2050, the Russian permafrost regions will be accumulating much more heat during the summer. Except for Chukotka all regions will be characterized by DDT values higher than those of present-day North European Russia, where permafrost is relatively warm. By the end of the century the regional-mean DDT everywhere in the Russian North is projected to rise well above the current DDT level in the warmest of all permafrost regions.

Maps in Figure 20 illustrate current (1990-2000 period, upper map) and projected for the mid-21st century (2040-2050 period, map in the middle) and end-21st century (2090-2100 period, lower map) annual-mean temperature in the near-surface permafrost layer. Magenta color highlights regions, where permafrost is projected to disappear in the near-surface layer. Projected warming, thawing and disappearance of the near-surface permafrost will have detrimental effect on various structures built upon it. Risks of infrastructure damage could be evaluated using the permafrost hazard index. This methodology and results of predictive risk modelling under different climate projections are presented in the series of publications (Anisimov, 2010; Anisimov and Belolutskaia, 2002; Anisimov and Reneva, 2006; Anisimov and Streletskiy, 2015; Nelson et al., 2001, 2002). Map in Figure 21 illustrates the regional distribution of the permafrost hazard index calculated using CMIP5 climate projection for mid-21st century. It delineates areas within Russian permafrost region with low, moderate and high risks to infrastructure.

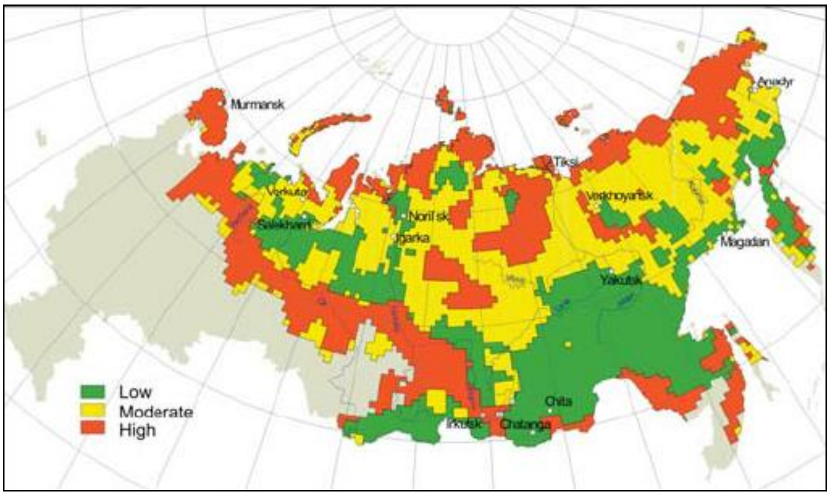


Figure 21. Permafrost hazard index for projected by mid-21st century climatic conditions.

The hazard index map provides useful information for adaptation planning. It highlights regions where investments and immediate engineering actions are needed to keep the currently existing infrastructure in a safe condition. Many tools have been developed in cold-region engineering to address such tasks, some of which are illustrated in Figure 22. Photos on the left show thermosyphones anchored in permafrost on both sides of the rail- and car roads on the Tibetan Plateau in China. Thermosyphone is a sealed tube filled with evaporating liquid. When anchored in permafrost, it acts in winter as a passive pump, effectively draining heat from the ground to the very cold air similarly to the way it is done in refrigerators, but at no energy cost. Photos on the right demonstrate even simpler technique, which employs the horizontal ventilating shafts in the body of the mound to chill it in winter. Such methods allow decreasing annual-mean ground temperature by few degrees C.

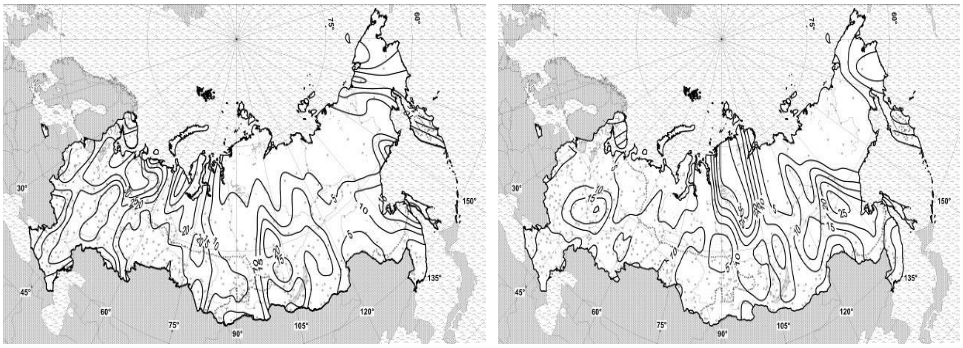
Figure 22. Engineering methods for keeping the infrastructure in permafrost regions.

Confidence and data quality

In the past few years there has been substantial evaluation of large-scale models of permafrost dynamics across the northern permafrost region, and we now have a better understanding of the range of uncertainty in projections associated with both models and future projections of climate change. There has also been progress in evaluating retrospective simulations of models at the sub-regional scale to identify which subset of models should be selected for quantifying uncertainty in future projections of permafrost dynamics. Progress has also been made in modeling the effects of vegetation change on permafrost dynamics in response to changing climate. Finally, there has been new progress in modeling the dynamics of sub-sea permafrost beneath the continental shelf of the Arctic Ocean.

There are two types of uncertainty in permafrost projections, the one associated with the forcing climate, soil, vegetation and other environmental data, and the other associates with the limitations of the permafrost models. The first type of uncertainty for Eurasian permafrost has been assessed in several studies (Anisimov 2011; Anisimov and Kokorev 2013; Anisimov et al. 2011, 2013; Kokorev and Anisimov 2013; Ziltcova and Anisimov 2013; Anisimov and Sherstukov 2016).

Anisimov and Sherstukov (2016) applied multifactoral regression analysis to climatic data from the full set of ca 1600 Russian and the former Soviet Union weather stations, and evaluated the contribution of air temperature and snow depth to the variation of the ground temperature in the period 1972-2012. Neither of these two factors accounted for more than 30% of the permafrost temperature variability (Figure 23), with air temperature playing more important role in the European Arctic region, and snow depth in Siberia.



A B

Figure 23. Percent of total ground temperature variability attributed to the air temperature (A) and snow depth (B). Anisimov and Sherstukov (2016).

Studies (Anisimov and Kokorev, 2013, 2016b; Kokorev and Anisimov, 2013) evaluated the skills of Earth System Models to model the impacts of climate variability and change on permafrost. Regional trends of several climatic parameters governing the state of permafrost were compared with 48 historical runs of CMIP5 Earth System Models, and models were ranked according to their skills (Figure 24, full data set is accessible at http://permafrost.su/gcm.html). Results were used to eliminate the outliers and construct the optimal ensemble consisting of models with "better than average" skills in Russian permafrost region. This procedure of sub-regional and process-specific evaluation of Earth System Models suggested in these studies markedly lowers the range of uncertainty in predictive permafrost modeling associated with climatic forcing.

Uncertainty of permafrost projections associated with changing vegetation has been evaluated in the studies (Anisimov and Sherstukov, 2016; Anisimov et al., 2015a). Vegetation acts as a moderator of the interactions between the atmospheric and permafrost thermal regime. The role of vegetation is two-fold. Non-vascular plants increase thermal insulation and protect permafrost from warming. Enhancement of the leaf area index of shrubs and trees also protects permafrost by attenuating the incident solar radiation. Interannual climate-driven variations of plant productivity thus attenuate the direct effect of temperature changes on permafrost.

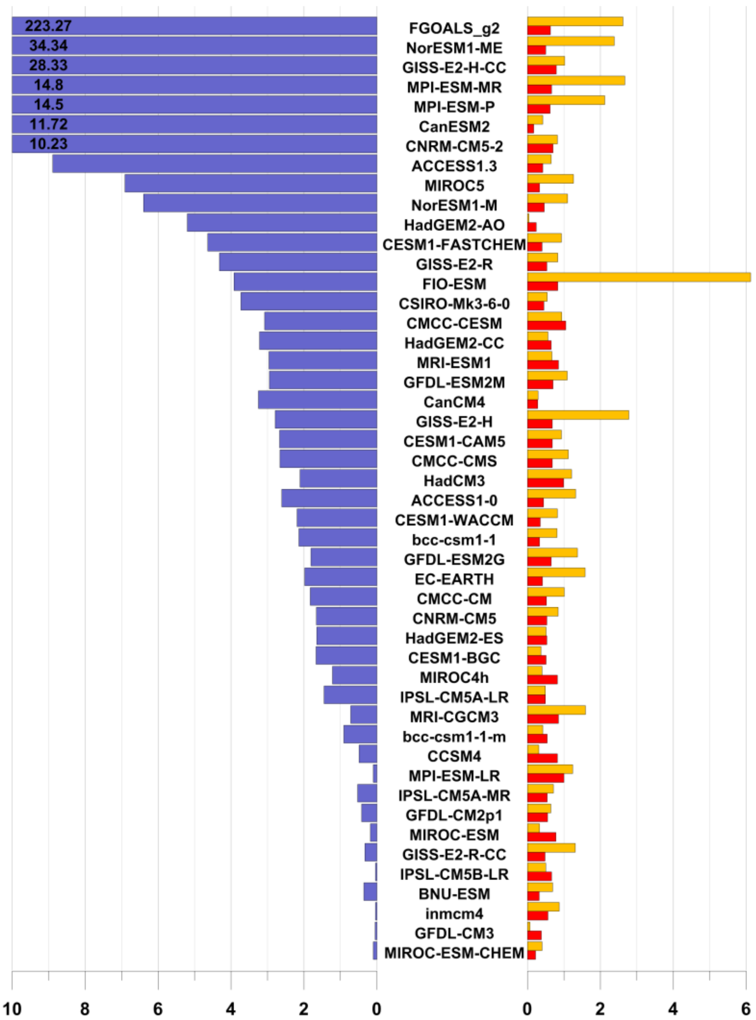


Figure 24. Departures of the CMIP5 GCMs-based trends from observations averaged over the Russian permafrost region. Blue – snow depth, 1976-2005 period; red and yellow – degree days of thawing for the 1976-2005 and 1941-1970 periods. Anisimov and Kokorev (2013).

Climate induced changes in vegetation, the effect of such changes on permafrost, and dynamically uncoupled climate-vegetation-permafrost modeling for Northern Eurasia have been assessed in several studies (Anisimov et al., 2011; Anisimov et al., 2015b; Ziltcova and Anisimov, 2013). These studies introduce the concept of region-specific critical climate thresholds, beyond which further climatic forcing leads to irreversible changes in the state of the vegetation-permafrost system. Critical thresholds, or tipping points, are characterized by shifts in the boundaries of biomes, introduction of new plant species, and abrupt changes in the permafrost thermal regime. Because of the difference in the response rates of permafrost temperature changes and biome boundaries shifts, the evolution of the system may be predicted using uncoupled stand-alone climate-driven permafrost and vegetation models. This approach was used to evaluate the percent of the permafrost area in four sectors of Russian permafrost regions that is likely to be affected by critical changes in the first half of the 21st century (Table 8).

Table 8. Fraction of the area in Russian permafrost regions (%) where vegetation-permafrost system is projected to pass the critical climate threshold by 2016-2045 and 2031-2060 time slices. Calculations were made using stand alone vegetation and permafrost models forced with the optimal CMIP5-based RCP-8.5 climate projection.

Time slice	European North	West Siberia	East Siberia	Chukotka	Eurasian permafrost average
2016-2045	58	64	55	48	56
2031-2060	71	74	70	57	67

Conclusions

To the extent that scientists, the business community, and policymakers around the world focus on the problem, their perception of climate change's impacts highlights the potentially detrimental consequences. Iconic examples from different regions include projected shortages of freshwater resources, reduction of agricultural yields, increased frequency and duration of heat waves, droughts and forest fires, spread of vector-borne diseases, thawing permafrost with deleterious impacts on infrastructure built upon it, and many more. In the past two decades the scientific community and policymakers were charged with managing the climate-related risks through developing adaptation strategies. In contrast to this, many consequences of the ongoing and projected climatic changes in Russian permafrost regions create new opportunities. Except for the effects of thawing permafrost on infrastructure, the climate challenges listed above are not applicable to the Arctic. Potential regional benefits have received significant attention in Russian studies, but are yet underrepresented in international publications. They are exemplified by less severe climatic conditions with direct implications for human health (Mokhov et al., 2013); a northward shift of the productive vegetation zones and a larger range of ecosystem services (Anisimov et al., 2016; Anisimov et al., 2011); a 3-5 day per decade average increase in the duration of the warm period with daily-mean temperatures above 10 °C so as the higher summer temperatures (Kattcov and Semenov, 2014); as a result, the northward advance of land suitable for agriculture, which is particularly important for sustainable regional development aimed at more intensive use of local resources; reduced demand for heating energy, with up to 5 days per decade reduction in the duration of the heating period in the past four decades (Kattcov and Semenov, 2014); dramatic reduction of the sea ice in the Arctic, at the average rate of 13 percent per decade, leading to a more navigable northern sea route (Khon and Mokhov, 2010); and increased water resources and a longer ice-free season on Great Siberian rivers, which in the absence of the developed road network serve as transportation corridors (Kattcov and Semenov, 2014). Taken together, such changes are likely to have the overall positive effect on the social and economic development of the region.

A comprehensive assessment of the balance between the negative and positive climate-induced changes in Russian permafrost regions is essentially lacking. The assertion of world-wide challenges presented by climate change becomes questionable, and is no longer accepted unequivocally by different population groups and stakeholders, especially those gaining immediate and often short-term benefits from the new regional opportunities. Although climate change is global in nature, the impacts are region-specific, and require adaptation options designed for the specific circumstances of regional systems, their susceptibility to climate change, and their ability to adapt. From this prospective, adaptation to climate change at the legislative level becomes a puzzle with no single approach across all settings.

Given that the Russian permafrost regions demonstrate the world-highest rates of climate change, the rate rather than the magnitude of change may become the key factor leading to dramatic impacts on natural and social systems, particularly if it exceeds the rate of their adaptation. On the other hand, uncertainty in climate projections remains large, which complicates adaptation planning. Under these circumstances most profitable are regional adaptation strategies that generate net social and economic benefits at no cost to other regions and sectors and irrespective of uncertainty in future forecasts (no-regret measures).

While climatic changes in Russian permafrost regions have already led to environmental and socio-economical impacts, it is still debatable whether climate change should become a matter of concern for the policymakers, business society, and population, and whether development of the climate adaptation policies should be given high priority. The problem is complicated by distinct differences in the public perception of the current and ongoing changes, and by the absence of societal preparedness to dedicated efforts to combat potentially detrimental consequences of the changing climate.

Even an ideal adaptation strategy based on the comprehensive and objective cost-benefit analysis would fail if it contradicts the public perception of the current and ongoing changes. This is especially true in Russian permafrost regions, where many people consider new Moscow-born legislative initiatives critically and with caution, and in case of a conflict with their own vision often sabotage them silently.

In recent years, scientists and researchers have been focused on providing advice to policy-makers working in various parts of the executive and legislative branches of government. However, even the best designed policies cannot advance if there is no public demand for them. Accordingly, it makes sense now for scientists to switch their focus from the supply side to the demand side. In other words, scientists should work to educate the public about basic scientific concepts so that they will begin to demand better policies from their public officials. Creating such demand will force governments to supply more policies that address the challenges presented by climate change. Creating such demand requires better communications in order to construct coalitions that will support such changes.

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