Permafrost and Infrastructure in the Usa Basin (Northeast European Russia): Possible Impacts of Global Warming

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The relationship between permafrost conditions and the distribution of infrastructure in the Usa Basin, Northeast European Russia, is analyzed. About 75% of the Basin is underlain by permafrost terrain with various degrees of continuity (isolated patches to continuous permafrost). The region has a high level of urban and industrial development (e.g., towns, coal mines, hydrocarbon extraction sites, railway, pipelines). GIS-analyses indicate that about 60% of all infrastructure is located in the 'high risk' permafrost area, here defined as the zones of isolated to discontinuous permafrost (3–90% coverage) with 'warm' ground temperatures (0 to -2°C). Ground monitoring, aerial photo interpretation, and permafrost modeling suggest a differential response to future global warming. Most of the permafrost-affected terrain will likely start to thaw within a few decades to a century. This forecast poses serious challenges to permafrost engineering and calls for long-term investments in adequate infrastructure that will pay back over time.

INTRODUCTION

Many regions in the northern taiga and arctic tundra are becoming heavily industrialized (e.g. European Russian Arctic, West and Central Siberia, Alaska). Oil and gas exploitation, coal and ore mining, and the accompanying road and settlement constructions are the main sources of infrastructure in these areas. In the northern regions of Russia, major towns are typically connected to the south by a network of railroads. It seems that regardless of the economic strategy chosen with respect to Russia's northern regions, these towns with infrastructure built during the Soviet period will serve as the centers for future development (1).

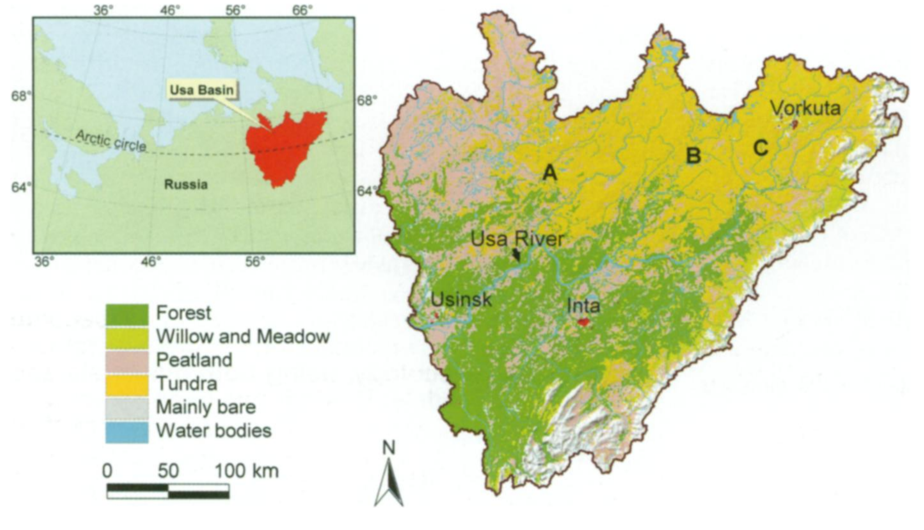

Figure 1. Map of the Usa Basin with topography (mountain shading effect), vegetation zones and main towns. The location of the Khoseda-Khard weather station (A), the Rogovaya River peat plateau (B) and the modeled permafrost sites (C) are also indicated.

Long-distance oil and gas pipelines are probably the most obvious feature of northern infrastructures. In Russia, most of these pipelines have been built in the 1970s–1980s. Due to the age of these pipelines and to natural environmental factors, numerous pipeline accidents have taken place (2).

Arctic regions are characterized by the occurrence of permafrost. In regions with a more oceanic type of climate, such as Fennoscandia and Northeast European Russia, the southern limits of permafrost are located much further north in comparison with more continental regions of the Northern Hemisphere, for example Eastern Siberia (3). The isolated to discontinuous 'warm' permafrost, widely distributed in Northeast European Russia, is very sensitive to changes in climate. Previous studies provided general predictions about the response of permafrost in the Circum-Arctic region to anticipated future global warming (4, 5). They indicate a significant increase in the active layer depth, retreat of the permafrost northwards and into deeper ground layers, and subsidence risks associated with permafrost thawing (6, 7).

This study was carried out in the framework of the INTAS-funded PERUSA project. The objectives of the paper are to present a detailed analysis of the relationships between permafrost conditions and the distribution of infrastructure in Northeast European Russia using a GIS-approach, and to evaluate the possible impacts of climate change on ground conditions using permafrost monitoring, aerial photo interpretation, and modeling techniques. Northeast European Russia is unique in continental Europe because of its extensive lowland permafrost. The region is known for its coal resources and is experiencing a rapid expansion of oil and gas activities (8).

STUDY AREA

For the purpose of this study we selected the Usa Basin, located in the Komi Republic and Nenets Region (Fig. 1). The Usa River is the largest tributary of the Pechora River, which flows to the Barents Sea. The entire Usa Basin occupies an area of about 93 500 km^2. About 85% of the area corresponds to lowlands with elevations below 200 m. The basin is delimited in the southeast and east by the Ural Mountains with the highest peak reaching an altitude of 1894 m. Forest in the southwestern and central lowlands occupies 25% of the total basin area. Tundra vegetation towards the north accounts for another 25%. Extensive peatlands can be found in both the taiga and tundra regions and cover 30% of the territory. The remaining area is occupied by meadows (2%), willow (7%), alpine areas (8%) and lakes (2%). Areas directly affected by human activities represent less than 1%.

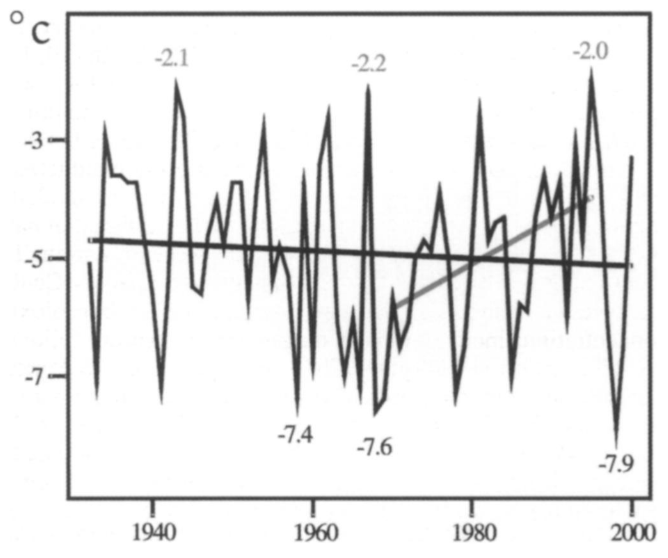

Figure 2. Mean annual air temperature at the Khoseda-Khard weather station, with warmest/coldest years and trends for the periods 1932-2000 and 1970-1995. Data from the Komi Republican Center for Hydrometeorological and Environmental Monitoring.

Mean annual air temperature in the Usa Basin lowlands varies from -2.5°C in the southwest to -6.5°C in the northeast. Figure 2 shows the mean annual air temperature record from 1932–2000 for the Khoseda-Khard weather station, which is located in the central part of the Usa Basin (for location see Fig. 1, site A). Over the last century, there has been considerable climatic variability, in some cases accounting for more than 5°C changes in mean annual air temperature from one year to the next (1966–1967–1968). There is no clear long-term trend in temperature between 1932–2000. The recent warming (1970–1995) was not exceptional compared to previous periods of the 20th century; similar high mean annual temperatures were recorded in 1943, 1967 and 1995. Furthermore, 1998 proved to be the coldest year on record in Khoseda-Khard and Vorkuta. An important conclusion is that conditions experienced during the later part of the 20th century were not exceptionally warm compared to the long-term observations in the area. An intercomparison of General Circulation Models (GCMs) shows a wide consensus indicating significant future warming amounting to 3°C or more by the end of the 21st century and increased precipitation for this part of the Arctic (9).

Most of the area has thick unconsolidated Quaternary deposits of glacial or glacial-marine origin, with the exception of the Ural foothills and mountains where these deposits are shallow over bedrock. The GIS 'Permafrost of the Usa Basin' shows that about 75% of its area is occupied by permafrost terrain with various degrees of discontinuity (10). About 75% of the total permafrost area corresponds to the zones of isolated, sporadic and discontinuous permafrost (here grouped under the term 'more discontinuous' permafrost). The temperatures of permafrost in these zones are between 0° and -2°C. Therefore, most of the Usa Basin (nearly 60%) is underlain by 'more discontinuous' and 'warm' permafrost. In this study, we define the zones of isolated, sporadic and discontinuous permafrost as 'high risk' areas because they are very sensitive to even moderate increases in temperature under expected future global warming. Ground temperatures may be as low as -4°C in the northernmost lowlands with continuous permafrost and can be even lower at high elevation in the Urals (10).

The region has extensive natural resources (e.g. coal, oil and gas fields). There are three large towns in the Usa Basin: Vorkuta, Inta and Usinsk. The main coalfields are near the towns of Vorkuta and Inta. Vorkuta became a town in 1943; with a population of 168 900 in 2001 (11), it is the center of the coal-mining industry in the region. Inta (population 59 400 in 2001) is a center of smaller coal mining enterprises. Oil and gas fields are mostly located in the (forest-) tundra north of the town of Usinsk (population 59 700 in 2001). Usinsk has been purposely developed for the oil and gas industry and became a town in 1984. Because of the remoteness of these towns and fields, fuels have to be transported by an extensive network of railroads and pipelines. The main railway connects the three towns with the large cities of the European Russian North. Roads are limited with the exception of the region north of Usinsk. With the economic downturn of the post-Soviet period, Vorkuta and Inta have been experiencing a decrease in coal production. The oil and gas extraction near the town of Usinsk, however, is expected to increase in the near future.

METHODS

A permafrost Geographical Information System (GIS) was developed for the Usa Basin expressing distribution, degree of discontinuity, temperatures, and specific landform features of permafrost (10). The topographic base was derived from digitized 1 : 200 000 topographic maps obtained from GOSGISCENTRE (Moscow). The GIS 'Permafrost of the Usa Basin' includes several thematic layers: stratigraphy (763 polygons, 12 classes), lithology (763 polygons, 8 classes), permafrost temperatures at the depth of zero annual amplitude and the degree of permafrost discontinuity (763 polygons, 9 temperature classes, 6 permafrost classes), reference boreholes (131 sites, each with more than 20 attributes), frost mounds with massive ice (28 points), massive ground-ice locations (11 points), and areas of intense thermokarst (70 points). The permafrost GIS shares its format and topographic base with other GIS data bases (e.g. climate, vegetation, soils) developed in the framework of the EC-funded TUNDRA project (Contract Nr. ENV4-CT97-0522) for the same basin, which allows sophisticated multidisciplinary analyses.

An important feature of this study is that conditions expressed in the permafrost GIS are representative of the period of recent warming between 1970–1995. A limited number of long-term ground temperature records that cover (most of) this period of time and characterize the main physiographic divisions and landforms of the study area were used to determine typical years. These typical years were determined as the years when temperatures deviated from the means for the period of interest by not more than a specified value. Then, only typical years were selected from the large number of short-term ground temperature records to complete the borehole reference dataset (10).

An infrastructure GIS for the Usa Basin is also available from the digitized 1:200 000 topographic maps (GOSGISCENTRE, Moscow). It includes settlements, roads and railroads, power lines and pipelines. It is important to mention that both the permafrost and infrastructure GIS layers mostly reflect conditions from the mid-1980s, because of the type of calibration technique used for permafrost characterization and because of the year of production of the GIS infrastructure data layers. Average climatic conditions have not changed substantially since that period. Because of the economic downturn since the collapse of the Soviet Union, very limited new infrastructure has been developed. The exceptions are some roads and pipelines constructed in recent years in the Usinsk and Khoseda-Khard areas (Fig. 1).

A close overlay analysis of the permafrost and infrastructure GIS databases using the same base area, projection method and geo-referencing allows the calculation of the percentage of different types of infrastructure on various zones of permafrost discriminating between mineral and peat deposits. Other important factors, such as the thickness and vertical structure of the cryolithozone and the thickness of the unconsolidated Meso-zoic-Cenozoic deposits were considered in the analysis, though corresponding GIS layers were not constructed as this was not possible within the framework of this study.

Recent thermokarst evolution was monitored in the discontinuous permafrost zone of the Usa Basin by comparing a 1961 US satellite image and a 1988 Soviet aerial photograph, using the Rogovaya River peat plateau area as an example (Fig. 1, site B).

Specific modeling of permafrost behavior was conducted at two sites representing the range of permafrost conditions in the discontinuous permafrost zone of the Usa Basin. They are located some 35 km to the southwest of Vorkuta (Fig. 1, site C). The site BP3 has a mineral soil of glacial-marine clayey loam with an upper organic horizon 5 cm thick. The active layer depth varied from 160 to 190 cm during the period 1970–1995. Seasonal freezing, however, reaches the permafrost table every year at this site (no talik has been developed yet). The mean ground temperature at a depth of zero amplitude is –1.05°C. Ground temperatures within the upper 160 cm were monitored at high temporal resolution from September 1998 to September 2000. The site LK3 is a peat plateau with the permafrost table at about 50 cm depth. Medium to well decomposed peat dominates the section with a total peat thickness close to 3 m. The high resolution temperature records for the upper 100 cm cover the period from August 1999 to September 2000. A similar peatland site located at 2 km from the LK3 site has a mean permafrost temperature of –1.95°C at a depth of zero amplitude. Permafrost and active layer temperatures are amongst the warmest at the loamy site BP3 and coldest at the peaty site LK3 for those observed in the zone of discontinuous permafrost in the Usa Basin (10, 12).

Future permafrost conditions for sites BP3 and LK3 were simulated for a period of 85 years using a transient, one-dimensional (depth) permafrost model (13, 14). The model has been calibrated for the period of extensive monitoring conducted at both locations. The climate scenario is a hybrid of modelled trends as provided by a GCM, superimposed by a signal of natural variability as provided by the Vorkuta weather station. The model output of the HadCM2S750 integration (Hadley Centre, UK) was used (15, 16). In this particular run, carbon dioxide concentrations increase rapidly during the 21st century followed by stabilization at 750 ppm. The gridpoint nearest to Vorkuta was selected. Trends in monthly temperature and precipitation, as provided by 30-year means for the periods 2010–2039, 2040–2069 and 2070–2099, were calculated as anomalies compared to the control run 1961–1990. The anomalies were then added (in temperature) or multiplied (in precipitation) to a record of observed climate variability at Vorkuta for the years 1948 to 1990 and back to 1948. By taking this symmetrical series, any trend was eliminated from the variability signal while still providing a unique sequence of climate change over the next 85 years. Some missing data in the Vorkuta series were obtained by correlation with the nearby Khoseda-Khard weather station. The result in terms of temperature has no trend in the first 25 years followed by rapid warming over the next 60 years (+3°C) and subsequent stabilization (at +4°C). This accommodates the effects of a possible near-term cooling due to a negative phase of the North Atlantic Oscillation (17) and the warming caused by increased greenhouse concentrations (15). Precipitation increases rapidly over the next 25 years, followed by stabilization. The monthly depth of snow cover, a critical parameter for permafrost modelling, was calculated by using a regression of winter precipitation against snow depth in meteorological data from the Vorkuta weather station.

The effects of global warming on permafrost can be derived from this hybrid climate scenario by looking at the consequences of temperature increases starting from around 2025. The climate changes predicted by HadCM2S750 are consistent with the results of other GCM experiments (9), but are smaller than the changes obtained by GCM runs using the newest IPCC (SRES) greenhouse gas concentrations and aerosol levels (18, 19).

The same climate change trends were used in the framework of the EC-funded TUNDRA project (Contract Nr. ENV4-CT97-0522) to obtain consistent scenarios of environmental change for the Usa Basin. The HadCM2S750 integration was used to analyze the effects of rapid warming during the 21st century and to assess the long-term new 'equilibrium' response to a warmer climate following stabilization (not applicable to this study).

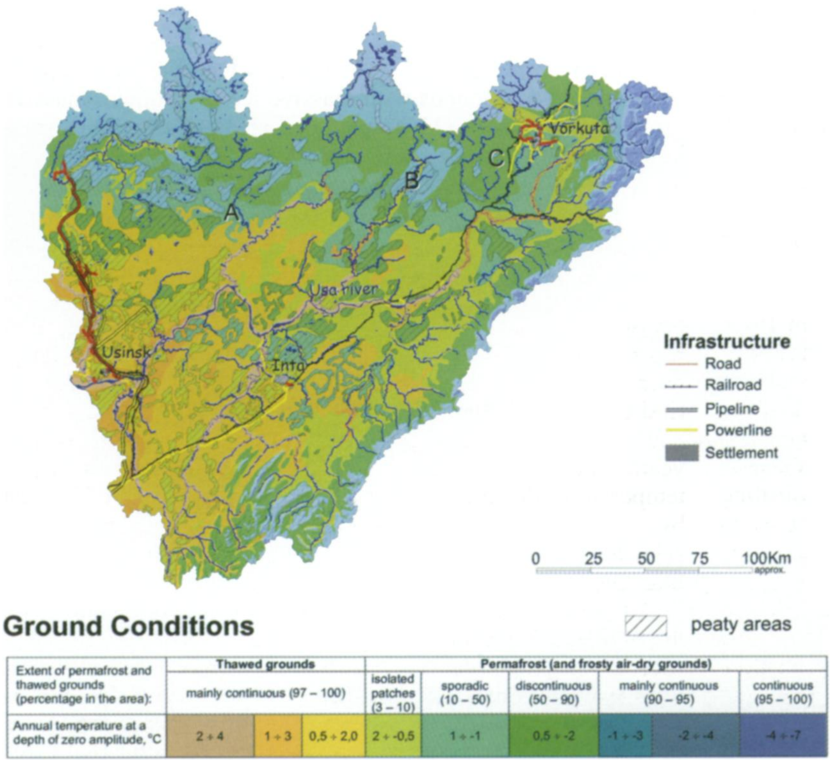

Figure 3. GIS overlay of permafrost conditions and infrastructure distribution in the Usa Basin.

Table 1. Total length and percentage of different types of infrastructure on 'high risk' permafrost and on 'high risk permafrost in peaty soil' in the Usa Basin. The analysis represents permafrost and infrastructure conditions for the mid-1980s.

Infrastructure type	Total length	Length on 'high risk'	Percent on 'high risk'	Length on 'high risk' and 'peaty'	Percent on 'high risk' and 'peaty'
Roads	328 km	198 km	60%	102 km	31%
Railroads *	851 km	525 km	62%	94 km	11%
Pipelines **	613 km	227 km	37%	184 km	30%
Powerlines	874 km	478 km	55%	184 km	21%

* The railroad is mostly single track, except near settlements. ** The pipelines can consist of multiple parallel installations.

RESULTS

Present-day Relationships

A GIS overlay of permafrost and infrastructure layers for the Usa Basin was performed (Fig. 3). Peaty areas are highlighted in the map by diagonal shading. The 'high risk' permafrost zone is defined in this study as 'warm' (0 to -2°C) permafrost-affected

View from a helicopter of a drilling installation and pipeline in peat plateau/thermokarst terrain north of Usinsk. (Photo P. Kuhry).

terrain with various degrees of discontinuity (3–90%). Table 1 gives the total length and percentage of infrastructure located on 'high risk' permafrost discriminating between mineral and peaty grounds. The percentages of different infrastructure types on 'high risk' permafrost in most cases exceed 50% of their total length (on average 54%). It is noteworthy to mention from this analysis that between 18–81% of infrastructure in the 'high risk' permafrost area is located on peaty grounds. Especially high percentages of peat grounds are found for roads (52%) and pipelines (81%).

The degree of risk for damage to infrastructure depends not only on permafrost temperatures. The texture of deposits, their ice content and thermal conductivity, and the thickness of unconsolidated surface deposits are also important. The greater the thickness, the higher the content of textural ice in the unconsolidated stratum, the more frozen water-bearing horizons the stratum contains. One of the dangers under conditions of permafrost degradation is presented by massive ground ice. The location of ice bodies, ranging in thickness between 1–3 m and at places more than 5 m, was mapped at several points (10). Based on the thickness of unconsolidated deposits, the Usa Basin can be subdivided into two groups of areas: *i)* thickness less than 20 (50) m; *ii)* thickness generally between 50–100 m, sometimes more. The first group encompasses the Urals, the adjacent 20 to 40 km-wide foothill plains, and the platform ridges Chernyshova and Chernova. The remaining part of the basin represents areas belonging to the second group. The higher ice content in the deposits of the latter areas can be derived from the numerous borehole data that show presence of bedded ice bodies at different depths and also from the larger number of thermokarst lakes (10).

The information on the vertical structure of the cryolithozone within the Usa Basin is also relevant to our analysis (20). Dominant permafrost thickness in the Ural foothills is 50 to 100 m. In the remaining part of the Basin, the cryolithozone is either two-layered or relict. In the former case, the upper permafrost layer is 50 to 100 m thick. It is separated from the relict permafrost layer by a regional intra-permafrost talik, which gives way to a regional supra-permafrost talik southwards. The thickness of both taliks varies from 30–50 to 100 m. The bottom of the cryolithozone in these areas is located at depths of 400 to 600 m. In the Urals, the dominant permafrost thickness ranges from 200 to 500 m. Hence, the permafrost in the Ural foothills and the upper permafrost layer in the remaining part of the Basin are most sensitive to climatic change.

The risk of damage to infrastructure is not restricted to progressive downward thawing of permafrost, which will be associated with ground subsidence. The lateral expansion of thermokarst lakes can also seriously threaten the existing infrastructure. A comparison of remote sensing images from 1961 and 1988 indicates that active thermokarst erosion and thermokarst drainage have taken place recently (not shown). In places, the lateral erosion of thermokarst lakes could pose serious economic and environmental risks (e.g. pipeline failures). For instance, oil platforms and pipelines north of Usinsk are built at places on peat plateau-thermokarst terrain (see photo). Despite recent warming, aggrading permafrost and associated frost heave was observed from the edges of recently drained thermokarst lakes inwards. The apparent paradox is explained by drastic changes in surface conditions that allow the penetration of winter cold in the newly exposed grounds after the drainage occurred.

Among urban areas, the infrastructure in Vorkuta is constructed on sporadic and discontinuous permafrost. Inta is mainly built on thawed grounds, however, some parts contain isolated patches of permafrost. Moreover, most of the developed area is situated on unstable clayey or peaty grounds. If these two towns should expand, problems could arise due to grounds unsuitable for construction. Usinsk is built completely on thawed grounds underlain at a greater depth by relict permafrost.

Permafrost Response to Global Warming

Permafrost engineers traditionally include in their planning a range of permafrost conditions related to observed climatic variability. Global warming will clearly affect the known range in permafrost conditions, but the time scale of change is important. The expected lifetime of oil and gas pipelines in the Russian Arctic is only 20–30 years. Other infrastructure in the Usa Basin was originally planned to last for a much longer period of time (e.g. urban infrastructure in the town of Vorkuta, the railway). Results of the modeling depict differential response to global warming in terms of active layer, talik development, and time lag after initial temperature increase. Ground temperature records covering the period of recent warming are in good agreement with this statement (21). Permafrost has generally warmed between 1970 and 1995, but at different degrees. Opposite trends were also observed, mostly in drained thermokarst lakes due to changes in surface conditions.

Figure 4 shows the modeled permafrost responses at two different sites to moderate global warming. In our climate scenario, the warming trend starts around 2025 (Fig. 4A). Active layer depth and talik formation are considered, as well as the time lag in the reactions. The two sites are representative of the Quaternary deposits most widely distributed in the Usa Basin, namely loam and peat. The 'warm and sensitive' BP3 site is located in upland tundra on loamy deposits. The cold and well-insulated LK3 site is a peat plateau. These two sites should characterize the range of responses to global warming that can be expected in the area of high risk permafrost. The permafrost at the BP3 site reacts very quickly (within 15 years) to the warming, but progressive thawing is quite slow due to energy consumed by the phase transition to liquid water. After 60 years of warming, the newly developed talik is only about 5 m deep (Fig. 4B). The LK3 site reacts more slowly to the warming, with the active layer becoming progressively thicker (Fig. 4C). A first, temporary talik is foreseen by 2083 (not shown), and, based on observed trends (not modeled), a permanent talik will likely form by the mid-2090s.

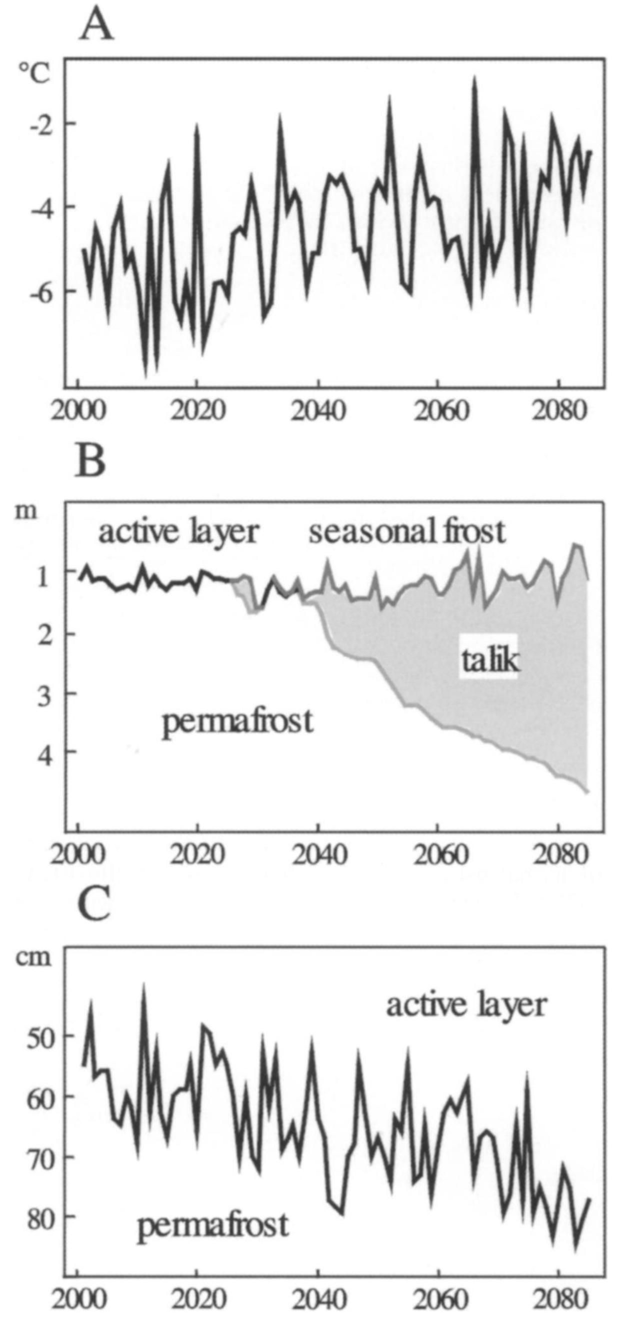

Figure 4. Modeled changes in the active layer depth and talik formation at two sites representing the range of conditions in the 'high risk' permafrost zones of the Usa Basin for the period 2000–2085 (A = changes in mean annual temperature; B = response at mineral site BP3; C = response at peaty site LK3).

DISCUSSION AND CONCLUSIONS

The 'warm' and 'more discontinuous' permafrost zones in the Usa Basin are highly sensitive to even moderate global warming, which in this study is estimated at about 3°C within the 21st century. The response of the permafrost in this high risk area will be differential based on physiographic and ground conditions (21). Generally, the result will be a ground subsidence (7), although temporary new permafrost aggradation and frost heave will occur under specific circumstances (e.g. drained thermokarst depressions). Changes in bearing capacity of the ground will affect the condition of infrastructure. Among urban areas Vorkuta faces most of the problems. The northern section of the Vorkuta railroad and the northern sections of the pipeline system are also under considerable risk.

Khroustalev (22) analyzed the potential failure of 5-story apartment buildings constructed in Vorkuta during 1950–1990. The temperature increase was assumed to be 0.75°C per decade (which is about twice as high as the warming rate derived from the GCM used in this study). The analysis shows that the lifetime of buildings would be much shorter than expected and numerous buildings would collapse as a result of climate change weakening the foundations.

Most of the existing transport and communication infrastructure in the Usa Basin will be affected by permafrost instability in the 21st century. Much of the newly planned development for the oil and gas sector is also in permafrost regions. According to modeling results, permafrost thawing and ground subsidence will commence in most cases within 10–60 years after global warming has started (in this study, 3°C in 60 years starting from 2025). The sensitive mineral site will likely react to the increased warming by developing a permanent talik within 15 years. The much colder peatland site is expected to react more slowly to the same warming developing a permanent talik in probably 70–75 years.

The conclusions from the above presented data are twofold: *i)* most permafrost sites will react to climate change at time scales between a decade and a century; *ii)* the evidence indicates a differential response of permafrost in various physiographic divisions and landforms to the same global warming, with even transient permafrost aggradation in newly drained thermokarst lakes. These temporal and spatial differences in permafrost response to anticipated warming pose serious challenges. Permafrost engineers should consider in their infrastructure planning and construction techniques the differential response of various permafrost terrains that will create entirely new conditions than those experienced in the recent past.

Future focus should be on the oil and gas pipelines, since damage can cause serious environmental disasters. To prevent this from happening, special safety measures and construction techniques must be used. The biggest problem with these techniques is not the willingness of engineers to use them but the higher costs. The only acceptable strategy is, nevertheless, long-term investments that will pay back over time. This is especially relevant in these times since high oil and gas prices have created extra incentives to develop the rich resources.

A key recommendation from this study is that regional governments and the international scientific community should support the continuation of existing and the initiation of new long-term permafrost monitoring projects in Northeast European Russia, because of the expected destabilization of permafrost and further intensification of the development in this region. Existing key boreholes at monitoring sites in the area of Vorkuta, already operating for the last 20–35 years and representing the range of landforms and parent materials in the region, should continue to operate. Long-term borehole permafrost monitoring should significantly expand in the tundra north of Usinsk and around the town of Naryan-Mar (Pechora Delta) because of the presence and expected large-scale further development of oil and gas fields with their accompanying installations (e.g. drilling towers, buildings, pipelines, roads).

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