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Authors: Streletskiy, Dmitry A., Shiklomanov, Nikolay I., and Nelson, Frederick E.

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Permafrost, Infrastructure, and Climate Change: a GIS-Based Landscape Approach to Geotechnical Modeling

Dmitry A. Streletskiy‡*
*Nikolay I. Shiklomanov**
and
Frederick E. Nelson†

*Department of Geography, George Washington University, 1922 F Street, NW, Washington, DC 20052, U.S.A.
†University of Delaware, Department of Geography, Newark, Delaware 19716, U.S.A.
‡Corresponding author: strelets@gwu.edu

Abstract

Increases in air temperature have occurred in most parts of the Arctic in recent decades. Corresponding changes in permafrost and the active layer have resulted in decreases in ground-bearing capacity, which may not have been anticipated at the time of construction in permafrost regions. Permafrost model was coupled with empirically derived solutions adopted from Soviet and Russian construction standards and regulations to estimate the bearing capacity of foundations under rapidly changing climatic conditions, in a variety of geographic and geologic settings. Changes in bearing capacity over the last 40 years were computed for large population and industrial centers within different physiographic and climatic conditions of the Russian Arctic. The largest decreases were found in city of Nadym, where the bearing capacity has decreased by more than 40%. A smaller, but considerable decrease of approximately 20% was estimated for Yakutsk and Salekhard. Spatial model results at a regional scale depict diverse patterns of changes in permafrost-bearing capacity in Northwest Siberia and the North Slope of Alaska. The most pronounced decreases in bearing capacity (more than 20%) are estimated for the southern part of permafrost zone where deformations of engineering structures can potentially be attributed to climate-induced permafrost warming.

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Introduction

Global climate change has been a key issue in world climatology over the last several decades. Recent scientific studies have improved our ability to understand and predict the impacts climate change may have on environmental and human systems. Many of the changes have potential to impact the natural environment, sectors of the economy, and socio-economic conditions adversely. Ongoing and anticipated changes in the climate system can expose the environment directly to risk and cause environmental changes that threaten human activities.

Many studies have provided discussion about the high vulnerability of northern environments to global climate change, and expressed concern that anthropogenic warming may have serious impacts on natural and human systems in the Arctic (Anisimov et al. [2010] and references cited therein). Although the prospect of climate change presents numerous challenges to human and natural systems throughout the world, there are few regions facing problems of the extent and severity of those affecting the high latitudes. Observational evidence indicates that impacts related to climate warming are well underway in the polar regions (ACIA, 2005; Anisimov et al., 2007). Problems arising from climate warming could be exacerbated locally by urban heat-island effects (e.g., Magee et al., 1999; Hinkel et al., 2003; Hinkel and Nelson, 2007; Klene et al., 2003).

Many of the potential environmental and socioeconomic impacts of global warming in the high northern latitudes are associated with *permafrost*, or perennially frozen ground. The permafrost regions occupy about 22.8×10^6 km^2 (24%) of the land area in the northern hemisphere (Fig. 1; Zhang et al., 1999). Major permafrost-related impacts have already been detected in many Arctic regions, including changes in the temperature (Clow, 2008; Burn and Zhang, 2009; Christiansen et al., 2010; Romanovsky et al., 2010a, 2010b) and distribution (Akerman and Johansson, 2008; Oberman, 2008; Oberman and Shesler, 2009) of permafrost, thickening of the active layer, the seasonally thawed stratum of earth material between the surface and the top of permafrost (e.g., Malkova, 2010; Smith at al., 2010), and changes in the distribution and quantity of ice in the ground (Vasiliev et al., 2008). Such changes in natural systems affect the human environment and have direct and immediate implications for land use, the economy, and human life in the Arctic (U.S. Arctic Research Commission, 2003).

Simultaneously, the Arctic experienced rapid economic development during the second half of the 20th century. Many of the changes are related to mineral resource exploration, which currently accounts for 10% and 25% of the world's oil and gas production, respectively. Despite its relatively small human population, the Arctic's share of the world economy is almost 0.5%, with more than two-thirds attributed to Russia (Anisimov et al., 2010). Mining camps, military bases, power grids, and roads have been constructed to support resource operations and provide quarters for remote populations, which collectively amount to more than four million people. The majority of these northern settlements contain relatively small populations, although several cities in the Russian Arctic have more than 100,000 inhabitants. About 80% of the settlements are located along the Arctic Ocean coast with the major exception of Siberia, where most of the settlements are historically located along major rivers (UNEP, 2005). Many of the settlements were built in permafrost terrain.

The majority of engineering structures on permafrost rely on ‘‘freezing strength'' or bearing capacity of the frozen ground to support structures. The mechanical bearing capacity of permafrost

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decreases with warming, causing weakening of foundations and potential damage to and possible failure of buildings, pipelines, and transportation facilities. Infrastructure in permafrost regions is also susceptible to thermokarst processes, which may cause uneven ground settlement and lead to deformation of buildings, economic disruption, and even loss of human life (Nelson et al., 2001, 2002). These factors make geocryological hazards a serious threat to the normal functioning of Arctic communities, and to economic development.

Incorporation of climate change projections for risk assessments of infrastructure on permafrost has become an increasingly important task over the last decade (Khrustalev and Shumilishskii, 1997; Lee, 2000; Nelson et. al., 2002; Instanes, 2003; Khrustalyov and Davidova, 2007; Clarke et al., 2008; Nishimura et al., 2009; Shmelev, 2010; Streletskiy, 2010). Recently, attempts have been made to incorporate economic considerations into analyses of climate change impacts (e.g., Larsen et al., 2008).

Climate change may, however, have already been taking its toll through deformation of engineered structures in Arctic regions. A survey of infrastructure in industrially developed parts of the Russian Arctic (Kronik, 2001) indicates that 10% of the buildings in Noril'sk, 22% in Tiksi, 55% in Dudinka, 35% in Dicson, 50% in Pevek and Amderma, 60% in Chita, and 80% in Vorkuta are in potentially dangerous states. Analysis of related accidents indicates that in the last decade they increased by 42% in the city of Noril'sk, 61% in Yakutsk, and 90% in Amderma.

A potentially dangerous situation has also been observed with respect to transportation routes and facilities. The long lateral extent of this type of infrastructure makes it difficult to choose an optimum route and apply economically sound strategies for controlling cryogenic processes (Garagulya, 1997). According to 1998 data, 46% of the roadbed under the Baikal-Amur railroad has been deformed by thawing of frozen ground, a 20% increase over the early 1990s (Kronik, 2001). Long-term (1970–2001) monitoring data from the Seyda-Vorkuta railroad indicate that the annual ground subsidence has increased from 10 to 15 cm in the mid-1970s to 50 cm in the mid-1990s. Correspondingly, during the same period the mean permafrost temperature along the railroad increased by 3–4 °C, from -6 or -7 °C to -3 °C (Anisimov et al., 2010). The condition of runways in Noril'sk, Yakutsk, Magadan, and other major Siberian cities are approaching states of emergency. Serious situations have been observed in gas and oil pipelines traversing the Russian north (Seligman, 1999, 2000). In 2001, for example, 16 breaks were reported on the Messoyakha-Noril'sk pipeline, causing significant economic and environmental damage (Kronik, 2001). Approximately 35,000 pipeline accidents of varying severity are reported annually in the oil and gas region of West Siberia. About 21% of these are thought to be attributable to mechanical deformation related to ground instability (Anisimov and Belolutskaya, 2002). For example, 1.5 m of vertical pipeline deformation was reported in the vicinity of Novuy Yrengoi. According to Oberman (2007), a pipeline accident in the Komi Republic in 1994 resulted from differential settlement of the ground surface. The results were six breaks in the pipeline and spillage of more than 160,000 tons of oil. This accident prompted extensive survey and reconstruction of several pipelines underlain by permafrost. The cost of maintenance, repair, and prevention of the pipeline deformation associated with changes in permafrost conditions are estimated at 55 billion rubles ($1.5 billion) annually (Anisimov et al., 2010).

In this paper, we use available observational data and modeling techniques to quantitatively evaluate the effects of ongoing climate change on structures built on permafrost, including large settlements in the Russian Arctic and regions of Northwest Siberia. Our goal is to test the proposition that the widespread deformation of buildings and structures already observed in permafrost regions is the result of diminished bearing capacity of permafrost soils induced by changes in climatic factors. It should be noted that, in many cases, it is difficult to differentiate between the effects of climate changes and other factors that may affect a structure on permafrost, such as age, lack of maintenance, or design/construction flaws. However, while other technogenic and environmental factors may or may not have contributed locally, climate change appears to be responsible for the broad patterns of these changes.

Background

The presence and dynamic nature of ice-rich permafrost constitutes a distinctive engineering environment (Andersland and Ladanyi, 2004; Muller, 2008). Many engineering problems in the Arctic are associated with: (1) changes in the temperature of the upper permafrost; (2) increased depth of seasonal thaw penetration; and (3) progressive thawing and disappearance of permafrost. These changes can lead to loss of soil-bearing strength, increased soil permeability, and increased potential for development of such cryogenic processes as differential thaw settlement and heave, destructive mass movements, and development of thermokarst terrain (Williams and Smith, 1989). Each of these phenomena has the capacity for severe negative consequences on human infrastructure in the high latitudes. Several factors are responsible for controlling the stability of ice-rich permafrost. These are primarily temperature at the top of the permafrost and the depth of seasonal thaw penetration. The rate and magnitude of thaw settlement is largely controlled by the volume of ground ice accumulated throughout local permafrost history.

Two common principles are used for construction design in permafrost environments (CNR, 1990; Grebenets and Rogov, 2000; Andersland and Ladanyi, 2004; Khrustalev; 2005, Shur and Goering, 2009; Gerasimov 2009). According to ''Principle I'' in Russia (the ''passive method'' in North America), permafrost is used as the base for foundations and is protected from thawing during the construction and maintenance of the structure. According to ''Principle II'' (the ''active method'' in North America), permafrost is thawed before or during the construction and the ground is thereby protected from permafrost aggradation during the life of the structure.

It is recommended that only one of the above principles is used inside any one construction area, such as a village, industrial plant, or city district. More than 75% of the buildings on permafrost in Russia were constructed using the first construction principle. Foundations are reinforced as they are incorporated in the permafrost (Grebenets and Rogov, 2000). Although the exact percentage of buildings constructed on permafrost using the passive principle in North America is not known, it is economically inefficient to thaw permafrost that is below −3 °C, limiting the use of the active method in areas of cold permafrost (Shur and Goering, 2009). Structures built according to the passive method are most susceptible to deformation.

The passive method of permafrost construction relies on ''freezing strength'' or bearing capacity of the frozen ground to support structures. Bearing capacity depends on the type of construction and is defined as the maximum stress that can be applied to the foundation without shear failure or catastrophic settlement (Tsytovich, 1975). The most common methods use piles to anchor structures in permafrost. The bearing capacity of a single post or pile depends on the contact between the side and base areas and permafrost, as well as the temperature of the surrounding medium. The area of the side contact with frozen ground depends on the thickness of the active layer. For a pile of given length, the thicker the active layer, the smaller the area in contact with permafrost, and the smaller the load that the pile can support. Increases in near-surface permafrost temperature and thickening of the active layer are likely to result in a decrease of the ability of foundations to support structures to a degree not anticipated at the time of construction. If the decreases are beyond the values of safety coefficients, deformation of foundations may result in severe damage to or even collapse of buildings and structures.

Because permafrost temperature and the thickness of the active layer depend on climate, engineering standards and designs have historically utilized the climatic ''normals'' (long-term mean values) available prior to construction. For instance, Soviet construction regulations recommended use of decadal climatic averages (CNR, 1990). The possible climatic variability and change are accounted in engineering procedures through a series of ''safety factors'' that decrease the uncertainties involved in describing the natural environment during construction. While safety coefficients in North America range from 2.5 to 3, in Soviet Russia they rarely exceeded 1.56, making many foundations in Russia especially vulnerable to climate change (Shur and Goering, 2009). The rapid change in climatic conditions raises questions about the stability of structures whose design is based on climatic normals from past decades and employed the relatively low safety coefficients used at the time of construction. Khrustalev (2000) analyzed the safety coefficient of foundations built using the ''passive method'' in Russia, as outlined in CNR (1990), and found that the safety coefficient varies from 1.05 to 1.56. Based on these values, if the bearing capacity of foundations under climatic, environmental, or technogenic factors decreases by 5 to 35%, a foundation will deform and the building may be subject to collapse. Using an arbitrarily chosen warming value of 1.5 °C, Khrustalev (2000) calculated bearing capacity for common foundation types in Yakutsk, concluding that such a relatively small increase in mean annual air temperature could be enough to trigger deformation of all foundations constructed in the city of Yakutsk.

Projected climate warming in the Arctic has potential to cause widespread deformation and damage to structures built in permafrost terrain. This could have severe socio-economic consequences because most existing infrastructure will require expensive engineering solutions to stabilize foundations (ACIA, 2005). This is especially true for the urban and industrial centers of Siberia, which were developed extensively in the late 1960s and early 1970s.

Although a decrease of foundation-bearing capacity attributable to permafrost warming is certainly plausible, other technogenic factors, such as disturbance and lack of maintenance, must be considered. Also, the high degree of heterogeneity in natural conditions and specific construction needs result in a wide diversity of engineering designs and practices. These factors make it impossible to fully assess the stability of infrastructure without a comprehensive engineering assessment of every structure. This enormous task is well beyond the scope of this study, which is instead focused on evaluating geographic changes in the engineering properties of frozen ground associated with observed climatic change. The analysis is based on Russian methodology, which utilizes bearing capacity for ''standard foundation piles'' embedded in permafrost as a primary variable for assessing engineering risks in permafrost-affected territory.

Methodology

EVALUATION OF NEAR-SURFACE PERMAFROST PARAMETERS

Numerical modeling, based on previously developed theoretical concepts and a growing database of regional permafrost studies, has become one of the dominant methodological approaches for understanding the variability of near-surface permafrost parameters over a wide range of scales. In this research, the methodology developed by Anisimov et al. (1997) was chosen as the basis for computation of temperature at the top of permafrost (TTOP) and active-layer thickness (ALT). The approach takes into account major geographical and geological factors and assumes a periodic, quasi-steady-state temperature regime. It is based on the modified Kudryavtsev solution (Kudryavtsev et al., 1974) to the general Stefan problem of heat conduction with a moving phase change boundary, and effectively accounts for the effects of snow cover, vegetation, soil moisture, ground thermal properties, and regional climate variations. This approach lends itself to the Russian tradition of landscape mapping and analysis (e.g., Shaw and Oldfield, 2007), and was also adopted by Shiklomanov and Nelson (1999), Sazonova and Romanovsky (2003), and Anisimov and Reneva (2006). Computational details are available in Anisimov et al. (1997) and Shiklomanov and Nelson (1999).

The model consists of five blocks (climate, snow, vegetation, organic layer, mineral soil) and a sequential algorithm of temperature calculations at the bottom of each layer. Several advantages are derived from this approach. One is that the warming effect of snow cover on ground temperature is calculated with respect to differences in the thermal properties of snow and the underlying soil substrate (Sazonova and Romanovsky, 2003). Another significant advantage is incorporation of an organic layer in the soil column and volumetric peat content in the ground. Introduction of the organic layer creates a two-layer system, which permits definition of the thermal characteristics of the soil and organic layers independently, while volumetric peat content can significantly influence the thermal properties of the ground. The thermal characteristics of each layer in the frozen and thawed states are different and assigned by granulometric and soil moisture content parameterization taken from CNR (1990) to be consistent with engineering procedures.

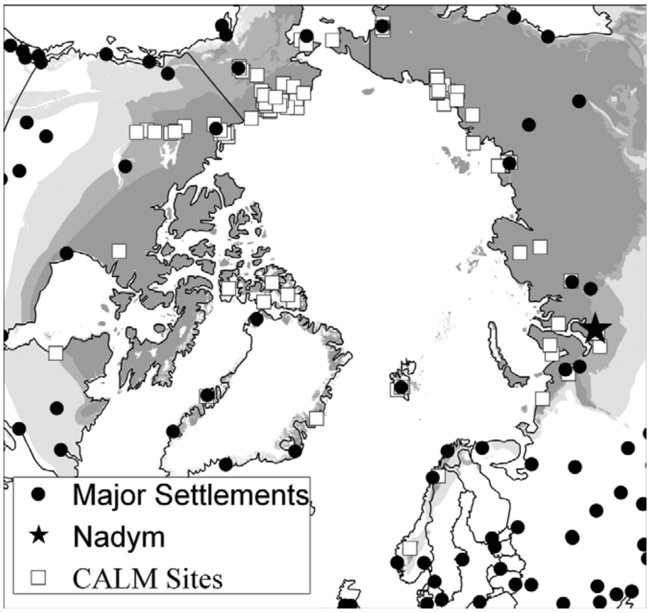

FIGURE 1. Major settlements in the Arctic and location of Circumpolar Active Layer Monitoring (CALM) sites. Location of Nadym in Northwest Siberia is indicated.

Model validation was performed at different scales, ranging from micro-landscape (1 m^2), through landscape unit (10–100 m^2), to landscape groups ($>$1000 m^2). Validation at the micro-landscape scale was performed for 121 points from the CALM (Circumpolar Active Layer Monitoring; Fig. 1) site R3 ''Marre-Salle,'' located on the west coast of the Yamal Peninsula in northwestern Siberia (CALM, 2010). Validation at the landscape scale was performed for sites representative of generalized landcover categories on the North Slope of Alaska (CALM sites U7b, U7c, U10, U11b, U11c; U12b, U31, U32a, U32b). Streletskiy et al. (2012) provided details about model evaluation and validation. In all cases monthly air temperature from automated monitoring stations located near the grids was used as atmospheric forcing (Streletskiy et al., 2008). Snow cover depth was derived from monthly Snow Water Equivalent at the 25 × 25 km grids representing each site (Armstrong et al., 2007). Vegetation (type and height) and soil properties (soil texture and moisture) collected at the sites (Walker and Bockheim, 1995) were used as parameterization for modeling.

Validation results have shown that the model works well in homogeneous micro-landscapes under zonal conditions. This is because the variability of environmental parameters is relatively low from year to year. However, modeled ALT differs significantly from observed values in those settings representing azonal conditions, such as water tracks, bogs, and peatlands. This situation arises from the high variability of snow and soil moisture in these landscapes, and cannot be resolved adequately at an annual scale. Weather conditions in particular years and perturbations of soil properties, such as moisture content, result in substantial discrepancies between predicted and observed values of active-layer thickness. The model overestimates ALT in years with extremely warm summers and underestimates ALT for years with summers colder than usual. At a temporal scale of several years, predicted values tend toward the observed climatic mean. Model error is proportional to the departure of annual climatic characteristics from established short-term means (5–10 years).

ANALYSIS OF BEARING CAPACITY OF FOUNDATIONS ON PERMAFROST

Ideally, every building foundation is designed to meet the best structural and economic criteria and hence is site specific. The characteristics of each foundation should not be reproduced at regional scales. Instead, one of the commonly used hypothetical piles can be used to analyze the freezing strength of foundations with permafrost in different geographic and geologic settings. In this research, a standard cement pile (0.35 × 0.35 × 10 m) was chosen as a reference for foundations. In this way, the bearing capacity of a standard foundation can be calculated as a continuous geographical field, facilitating spatial analysis.

According to Russian construction standards, foundations in permafrost regions are required to satisfy the condition (CNR, 1990):

$$N \geq F_u \gamma_n, \tag{1}$$

where N is the assumed load on the foundation; F_u is the bearing capacity of the foundation; and γ_n is a safety factor.

The bearing capacity of a foundation is represented as the sum of normal stresses at the base of the pile and shear stress at the pile sides in contact with permafrost. The bearing capacity of a vertically loaded friction pile or bearing post in permafrost with low ice content is defined as (CNR, 1990):

$$F_u = \gamma_t \gamma_c \left(RA + \sum_{i=1}^{n} R_{af,i} A_{af,i} \right). \tag{2}$$

and, with high ice content, it is equal to:

$$F_u = \gamma_t \gamma_c \left(RA + \sum_{i=j}^{n} ((1 - i_j) R_{sh,j} + i_j R_{sh,1,j}) A_{sh,j} \right), \tag{3}$$

where γ_t is a temperature coefficient accounting for potential changes in the ground thermal regime after construction ($\gamma_t = 1.0$ in most cases, but $\gamma_t = 0.8$ for pipelines). γ_c is a production coefficient equal to 1.0 for most cases; R represents normal stresses generated at the base of the pile (kPa); A is bottom area of the bearing post or pile at its contact with the ground (m^2); $R_{af,i}$ represents shear stresses generated along the shaft of the pile at a contact with layer i (kPa); $A_{af,i}$ is the area of the side contact of a pile with frozen ground (m^2); n is the number of different layers of permafrost in contact with the pile; i_j is ice content of the jth layer; $R_{sh,j}$ and $R_{sh,i,j}$ are shear stresses on a pile with special cement solution at a side contact for the jth layer (kPa); and $A_{sh,j}$ is the area of side contact of pile with ground in layer j (m^2).

Both the normal stress generated at the base of a pile and shear stress along the pile will be smallest when the ground temperature is at its maximum value, as higher temperatures will lower the cohesion of the ground because the amount of unfrozen water is higher. In the case of homogeneous ground, the average shear stress is applied to the point of the pile located halfway between the bottom of the pile and the top of permafrost. The ground temperature at this location is called ''equivalent temperature'' (T_e).

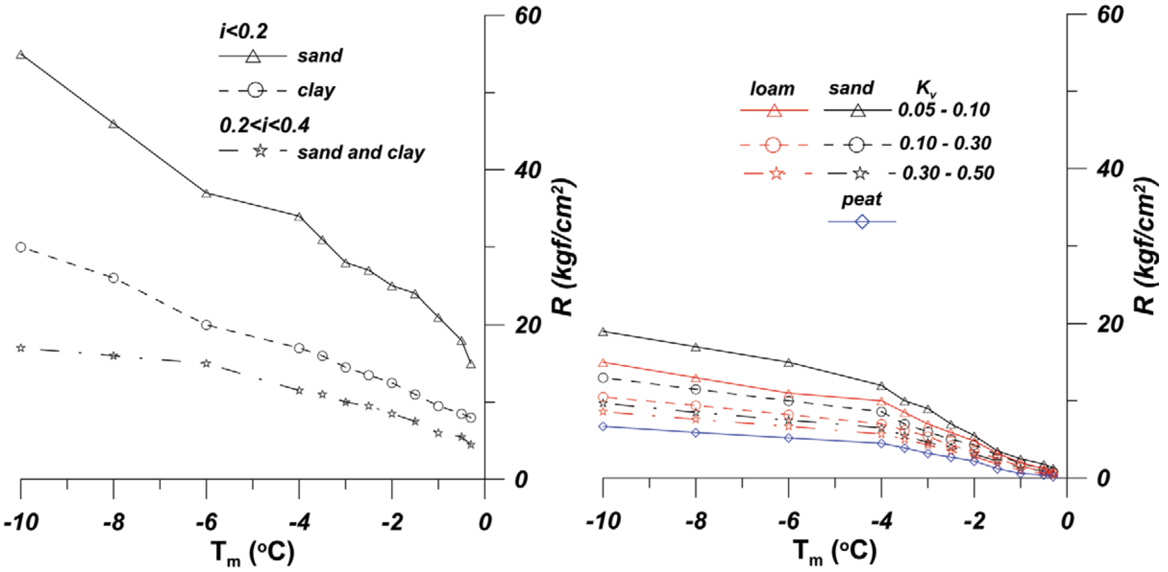

FIGURE 2. Normal stresses (R) generated at the base of a 10 m pile, depending on maximum ground temperature at the bottom of the pile, composed for different types of soil texture and ice content (left), and volumetric peat content (right). Based on data from CNR (1990).

CNR (1990) provides experimental values required for calculating bearing capacity in the form of tables, which were implemented in the model as a series of empirically derived equations accounting for changes in normal stress generated at the bottom of the pile, depending on maximum ground temperature (T_m), different texture, ice content, and volumetric fraction of peat in mineral ground (Fig. 2). When the ground has high ice content it is recommended that a special cement solution be used to fill the borehole prior to installation of the pile. The shear stress of a pile with special solution R_{sh} is used when ice content exceeds 20% by volume. Figure 3 shows dependence of shear stress on equivalent temperature (T_e) for different types of ground and ice conditions. High ice content ($i > 0.2$) and the presence of peat significantly decrease normal and shear stresses generated at the contact of the pile with permafrost. While CNR (1990) provides empirical data on dependence of freezing temperature on salinity for typical soils, dependence of unfrozen water on ground temperature is only evaluated for non-saline ground.

Absence of data on permafrost thickness and geothermal gradients at most locations creates uncertainty in estimating temperature at the pile depth, as lower boundary conditions for temperature calculations cannot be defined under such circumstances. At the same time, warming of permafrost creates non-equilibrium ground temperature profiles, when TTOP is slightly higher than at the depth

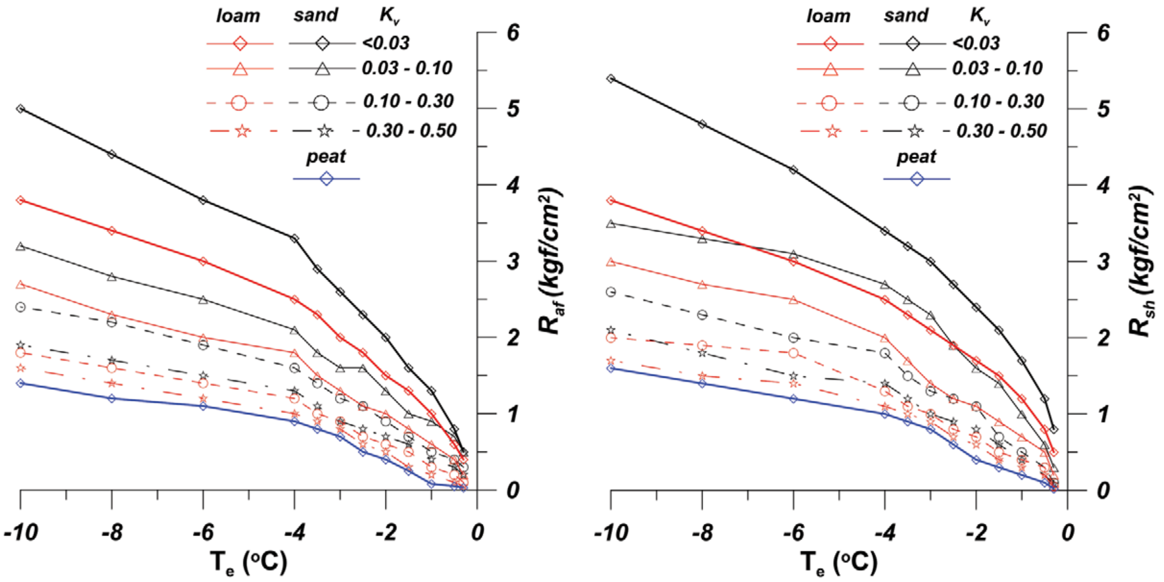

FIGURE 3. Shear stresses generated at the side contact of pile and (left) permafrost (R_{af}) and (right) special ground solution (R_{sh}) depending on equivalent temperature of the ground for different types of soil texture, ice content relative value of peat content. Based on data from CNR (1990).

of zero amplitude variation in most boreholes (V. Romanovsky, personal communication, October 2010). This fact allows use of TTOP rather than T_z to produce conservative estimates of bearing capacity, and is used for regional applications of the model when information about permafrost thickness is unavailable. The interannual variability of TTOP can be high (especially in cold permafrost) so it is preferable to use multi-year averages for TTOP. After T_z has been calculated, an estimate of the maximum annual ground temperature at the bottom of the pile (T_m) is obtained based on empirical relationships published in CNR (1990). There are two major limitations in the method. The model currently is not sensitive to changes in ground temperatures below -10 °C. However, contemporary permafrost temperature is higher at most northern hemisphere locations, with the exceptions of the Canadian Arctic Archipelago and the Russian High Arctic (Romanovsky et al., 2010b). Currently, the model assumes that permafrost will be absent if temperature at its top is higher than 0 °C, and prescribes values of normal (R) and shear stress (R_{af}) obtained for loamy sand in non-permafrost areas.

Results and Discussion

FOCUS AREA: NADYM

Changes in bearing capacity under observed climatic changes were analyzed in major industrial centers and settlements. One of the largest cities in Northwest Siberia is Nadym (Fig. 1), with a population of about 50,000 people. Nadym was built at the site of a previous small settlement at the beginning of the 1970s, after discovery of the Medvejie gas condensate field. Climatic averages of the pre-1970 decade were apparently used to estimate the bearing capacity of piling foundations prior to the construction of the town. Comparison of mean annual air temperature obtained for the Nadym weather station from the 1960s and 1990s shows that the latter was about 1.5 °C warmer. Such pronounced warming is likely to cause a substantial decrease in bearing capacity. Changes in bearing capacity associated with air temperature changes were estimated based on meteorological data from the Nadym weather station available for the 1963–2010 period (RIHMI, 2011). It was assumed that heat exchange under buildings is a direct function of changes in air temperature, as ground cover (primarily vegetation and snow) are absent under the buildings. The soil profile was assumed to be a homogeneous sandy loam with gravimetric soil moisture content of 30% (Melnikov et al., 1983). Calculated bearing capacity is shown in percent, relative to average bearing capacity for the 1963–1970 period (Fig. 4). Substantial year-to-year variation in bearing capacity occurs through climatic variability, but there is a general declining trend. During the 1970s, bearing capacity decreased by less than 7% compared to the 1960s, but by about 23% in the 1980s. Climatic conditions in the 1990s did not change relative to the 1980s, so bearing capacity did not decrease during that decade. However, a warming trend in the 2000s resulted in a dramatic decrease in bearing capacity—up to 33% compared to the 1960s. This agrees well with another study conducted in Vorkuta (Oberman and Shesler, 2009), according to which catastrophic deformation of buildings was confined to the 1980s, the period with the greatest increase of temperatures in permafrost composed of Quaternary mineral deposits and peat.

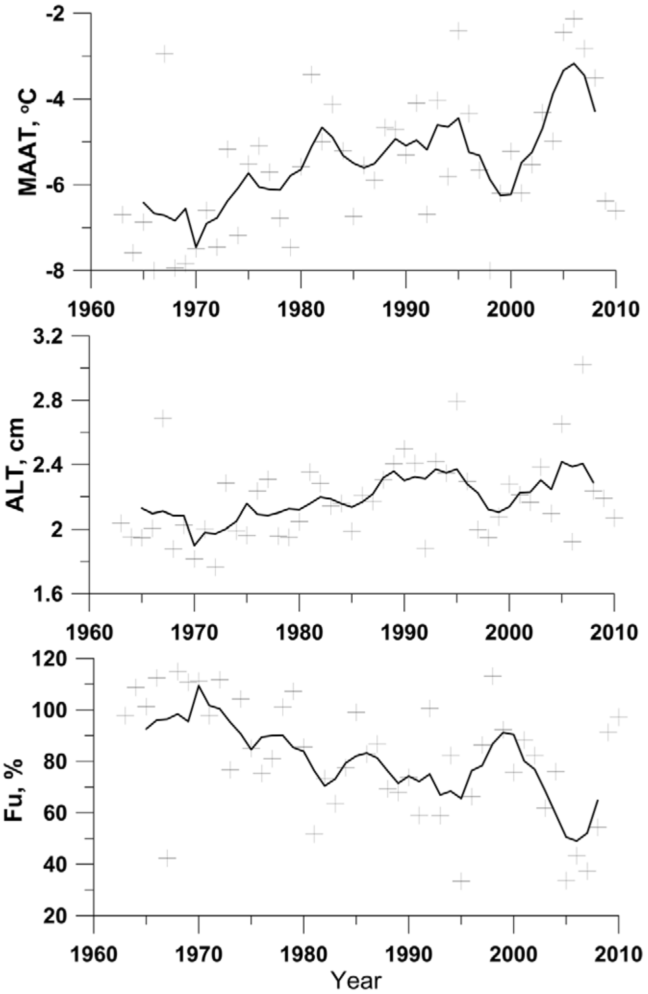

FIGURE 4. Observed changes of mean annual air temperature (MAAT) and associated computed changes of active-layer thickness (ALT) and bearing capacity (F_u) for the Nadym region. Black crosses represent estimated annual values. Solid line shows 5-year running average. All trends are significant at $p < 0.01$.

LARGE POPULATION CENTERS ON PERMAFROST

Changes in bearing capacity were calculated for other large settlements on permafrost, representing different parts of the Russian Arctic. Locations were chosen based on the assumption that if modeled temperature at the top of permafrost was less than -3 °C during the 1960s, the foundations were built based on the first (passive) principle.

Monthly air temperature data from weather stations located within each settlement were used as input and therefore incorporate possible urban heat-island effects. All stations are part of the Russian Hydrometeorological network (RIHMI, 2011). Data from 1960 to 2010 were used for the majority of settlements, except Norilsk and Chersky (1960 to 2005). Table 1 shows five-year means of changes in mean annual air temperature relative to 1960–1964 period for each of the settlements. It was assumed that with adequate maintenance of the building, annual temperature at the ground surface approaches that of the air. No snow cover was assumed to be present beneath structures and no engineering solutions were implemented to control ground temperature (e.g., thermosyphons).

TABLE 1

Changes of mean annual air temperature (MAAT) relative to 1960–1964.

		MAAT (°C)	Change of MAAT relative to 1960–1964, °C								
Region	Settlement	1960–1964	1965–1979	1970–1974	1975–1979	1980–1984	1985–1989	1990–1994	1995–1999	2000–2005	2005–2010
West Siberia	Salekhard	−6.7	−0.5	−0.6	−0.2	1.1	0.6	1.1	1.0	1.4	1.1
	Nadym	−7.1	0.4	0.4	1.0	2.5	1.6	2.0	1.8	2.4	3.2
	Noviy Port	−8.4	−0.8	−1.1	−0.5	0.7	0.1	0.3	0.4	0.8	1.0
Central Siberia	Noril'sk	−9.6	−0.9	−1.1	−0.5	0.7	0.3	0.5	0.8	0.2	NA
	Dudinka	−10.3	−0.5	−0.7	−0.2	1.1	0.6	0.8	1.1	0.7	1.4
East Siberia	Yakutsk	−10.1	−0.8	−0.2	0.0	0.3	0.7	1.3	1.6	1.6	2.3
	Tiksi	−13.4	−0.1	0.1	−0.6	0.3	0.1	1.0	0.0	0.5	1.7
	Anadyr	−7.4	−0.1	−0.3	−0.6	0.1	−0.2	0.0	0.7	1.1	0.7
	Chersky	−11.7	−0.1	0.2	−0.4	0.2	0.5	0.3	0.6	2.0	NA

Ground properties can be quite variable inside each settlement. For each location, the ground was assumed to consist of sand, sandy loam, or clay. In each case high and low estimates of ice content were applied. According to CNR (1990), low ice content is defined as below 0.2 (20%) and high ice content is above 0.4. We used values of 0.0 and 0.4, respectively. After six iterations a characteristic range of bearing capacity was therefore produced for each settlement. Annual values were averaged to produce five-year means. Average bearing capacity for 1960–1965 was chosen as a reference point representing 100%. The percent change was calculated relative to this reference for the series of years represented in Table 2.

Foundation-bearing capacity is quite variable, even at short temporal scales. The ends of the 1960s and 1970s decades were colder than the first half of the 1960s, resulting in an increase in bearing capacity. Following the general warming observed at all sites, especially in West Siberia, a decreasing trend in bearing capacity occurred, beginning in the 1980s. The first half of the 1980s and the second half of the 2000s had the largest increases of air temperature and substantial loss of foundation bearing capacity. Similar warming results in a more substantial decrease in bearing capacity in the southern part of the permafrost region, where ground temperatures are warmer than in northern locations. Nadym and Salekhard, for example, are subject to similar climatic conditions. However, the substantially more pronounced warming trend observed in Nadym resulted in a much greater decrease in bearing capacity than at Salekhard (46% and 19%, respectively). A similar contrast is evident through comparison of Noviy Port, Dudinka, and Anadyr. All three cities showed a 12% decrease in bearing capacity by the end of 2000s, although Dudinka experienced a larger magnitude of warming than did Anadyr (+1.4 °C and +0.7 °C, respectively). Anadyr is located in an area of warmer climate and permafrost. This geographic pattern shows that areas located in the southern part of the permafrost region (TTOP higher than −5 °C) are likely to experience more pronounced decreases in bearing capacity under projections of climate warming.

REGIONAL STUDIES

Evaluation of near-surface permafrost at regional scales is one of the most difficult tasks of modern geocryology. Unlike modeling at local scales, where input data for landscape parameters are available, or modeling at the circumpolar scale, where the variability of near-surface permafrost can be represented effectively by climatic input, modeling at regional scales requires solid knowledge of both. While the quality of output modeling fields depends directly on that of the model parameterization, differences in climatic input and landcover characteristics can significantly influence the results.

TABLE 2

Changes in foundation bearing capacity (BC) attributable to observed climate change, relative to 1960–1964.

		BC (tons)	Change of BC of foundations relative to 1960–1964, %								
Region	Settlement	1960–1964	1965–1979	1970–1974	1975–1979	1980–1984	1985–1989	1990–1994	1995–1999	2000–2005	2005–2010
West Siberia	Salekhard	178–333	6	10	3	−15	−8	−18	−15	−22	−19
	Nadym	184 − 343	−7	−3	−14	−34	−23	−29	−26	−35	−46
	Noviy Port	224 − 410	6	12	5	−6	−1	−4	−5	−9	−12
Central Siberia	Noril'sk	245 − 450	2	6	1	−6	−3	−5	−6	−3	NA
	Dudinka	255 − 468	1	5	1	−6	−4	−5	−7	−6	−12
East Siberia	Yakutsk	228 − 420	5	1	1	−2	−7	−11	−14	−15	−21
	Tiksi	304 − 560	−2	−2	0	−2	−1	−4	−1	−4	−6
	Anadyr	207 − 382	1	3	5	0	1	−3	−11	−17	−12
	Chersky	277 − 510	−1	−3	2	0	−4	−4	−4	−14	NA

Here, we address these questions by providing methodological approaches to the problem of modeling near-surface permafrost parameters for two study regions by utilizing available observational data, GIS, and modeling techniques to evaluate the spatial variability of near-surface permafrost parameters under observed and projected climate change, and over geographically extensive areas.

Assessment of changes in foundation-bearing capacity is given for two important Arctic regions, both of which contribute a substantial amount of oil and gas production and have relatively well-developed infrastructure. Climatic and environmental data in these regions are of different detail, geographic coverage, and temporal resolution, reflecting slight differences in methodological approaches. Owing to historical differences, both the analytical solutions and safety factors are different in Western and Soviet engineering schools. While construction codes and manuals in the West exist mainly to inform, advise, and guide engineers, the same types of documents had the force of law, with obligatory compliance, in the USSR (Fish, 1983) and, until recently, in Russia. This situation is reflected in the higher freedom of decision making afforded Western engineers, but also the higher degree of responsibility as compared to Russian engineers. Strict compliance with a government-established set of norms and procedures allowed little freedom in decision making in the USSR outside established government limits. Risk minimization has a somewhat higher priority than economic efficiency in the Western school, as compared to Soviet counterparts. This is, arguably, a reason for the much higher safety coefficients in North America.

North Slope of Alaska

Climate data for model input were obtained from *Scenarios Network for Alaska Planning* (SNAP, 2010). The SNAP data set is based on downscaled output from the five general circulation models (GCMs) employed by the Intergovernmental Panel on Climate Change (Christensen et al., 2007) with the best performance for this region. The model output consists of monthly values of air temperature and precipitation and spans the 1980–2099 period. The data set covers the entire state of Alaska with a resolution of 2 km^2. Analysis of short-term climatic changes in near-surface permafrost characteristics was performed based on a parameterization developed using CALM observation data and a landcover map of the North Slope of Alaska (Walker and Muller, 1999). The original landcover map of 1 ha resolution was degraded to 2 km^2 resolution, as used by SNAP. The landcover class with the highest frequency was chosen to represent each 2 × 2 km grid element. Three decades were used to address historical changes and provide a forecast of changing permafrost conditions: 1990s, 2020s, and 2040s. The forecast is based on a SNAP ensemble for the A1B scenario.

According to the A1B scenario, annual air temperature on the North Slope of Alaska (NSA) will increase by 1–2 °C by 2020 and by 3–4.5 °C by 2040, relative to 1980 (Fig. 5, part a). The western part of NSA will experience warming at a higher rate compared to the eastern, more continental, part. Snow-cover depth will increase in most of NSA. A 5–10 cm increase is projected by 2020, with the exception of the northernmost part (Barrow area) and both the northern and southern slopes of the Brooks Range. This tendency is forecast to continue in the 2040s, with further increases of snow depth throughout the coastal plain and foothills area, and decreased snow cover in the Brooks Range (Fig. 5, part b).

Increasing air temperature and snow cover depth will, in turn, increase TTOP and thicken the active layer. TTOP will increase by about 3 °C in the western coastal areas and by less than 1 °C in the eastern part by 2020. The Arctic coast, Brooks Range, and much of the eastern part will experience a 1–1.5 °C increase in TTOP. In the central area, TTOP will increase by 1.3–2 °C (Fig. 5, part c). Estimated changes in ALT are for non-mountainous areas to show less than 10 cm thickening, while non-vegetated areas of the Brooks Range will experience three times more. Moist non-acidic tundra shows a slightly higher response to the warming. By 2040, estimated changes in permafrost parameters will be more pronounced. TTOP will increase by more than 3 °C, with the exception of the Barrow area and the northeast (2.5–3 °C). In most of the foothills and coastal plain, the projected increase in ALT is 20–30 cm, with the exception of river floodplains and deltas and less vegetated outcrops, where it is 30–40 cm (Fig. 5, part d). Unvegetated areas of the Brooks Range show a 40–55 cm increase relative to 1980. The calculated spatial average for NSA is 0.65 m in 1980, 0.78 in 2000, 0.76 m in 2020, and 0.98 m in 2040.

The projected increase in TTOP and ALT will decrease the bearing capacity of foundations throughout the North Slope. The largest decreases are expected in the southwestern part of NSA (Fig. 5, part e). If the spatial average of bearing capacity in 1980 is considered to be 100%, its relative decrease in 2000 is 22%, in 2020 is 26%, and in 2040 is 52%. This indicates that, regionally, foundations built in 1980 will be able to support 25% less structural load by the end of the next decade, and that by the middle of the century the ground will lose more than half the bearing capacity anticipated at the time of construction. Although the high safety coefficients used in the U.S.A. are much higher (usually 200 to 300%), deformation because of ground subsidence can still be expected in areas with high ice content.

Northwest Siberia

Widespread deformation of buildings in this region has been attributed to the situation during the late 1980s and early 1990s, a time of great economic and social stress that resulted in poor maintenance of many structures. To answer the question of whether climate change alone can be responsible for this widespread decrease of foundation-bearing capacity or whether socio-economic factors played a major role, it was hypothesized that climatic normals for the 1960s were used at the time of construction.

Northwest Siberia is covered somewhat better by meteorological stations than is the North Slope of Alaska. The absence of large topographic barriers in the region creates a primarily zonal distribution of air temperature. Owing to the position of the Ural Mountains, precipitation increases from NW to SE. Comparison of commonly used climatic gridded data sets shows good agreement in the region, so the choice between climate data sets used for the temporal analysis is not as important as in other regions (Streletskiy, 2010). For this study, the University of Delaware Terrestrial Air Temperature: 1900–2008 Gridded Monthly Time Series v.2.01 (Matsuura and Willmott, 2009) was used as climatic input to compare the decades of the 1960s and 2000s.

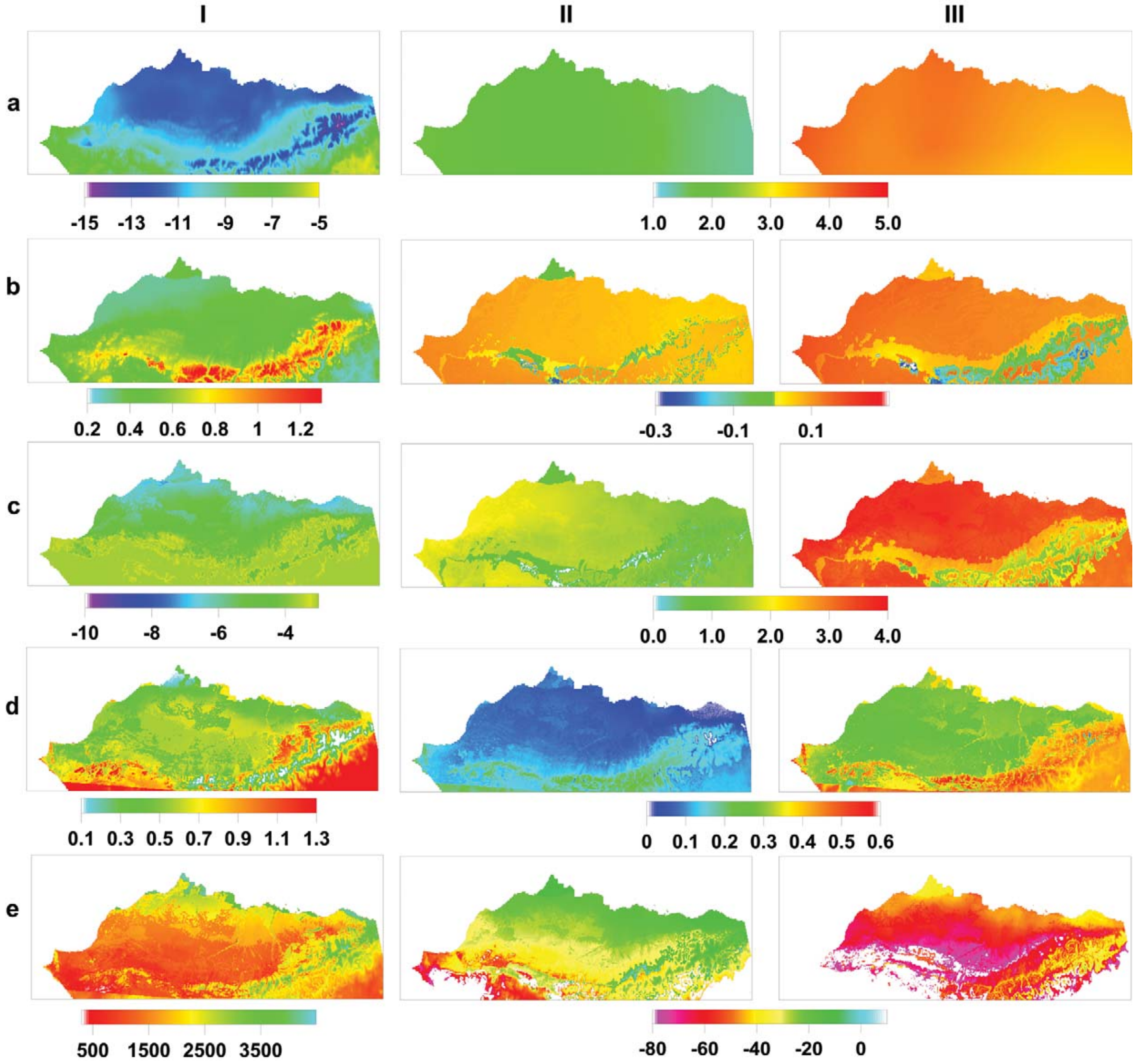

FIGURE 5. Climatic variability and near-surface permafrost conditions in 1980 (I) and relative projected changes of these conditions by 2020 (II) and 2040 (III): (a) mean annual air temperature (°C); (b) snow depth (m); (c) TTOP (°C); (d) ALT (cm); (e) bearing capacity (*kN*, changes shown in percent). Note: color progression is proportional to hazard potential—blue indicates stability, red and violet indicate increasing instability.

Environmental variables required for model parameterization were derived from *The Landscape Map of Northwest Siberia* (D. S. Drozdov, unpublished material) and include soil texture, peat content, and ice content. The map was downscaled to 1 km resolution (Streletskiy, 2010). This resolution was chosen as adequate to represent the geographic variability of near-surface permafrost parameters at the landscape scale (Melnikov et al., 1983). Additional information, where missing, was obtained from Trofimov (1987), and Melnikov et al. (1983). Soil texture, where missing, was assigned the value for sandy loam (1400 kg/m^3).

The resulting maps (Fig. 6) show regional changes between the two decades for mean annual air temperature, mean annual ground temperature, ALT, and foundation-bearing capacity. Analysis of the MAAT difference field shows that, regionally, temperature increased by 1.68 ± 0.16 °C between the two reference periods. The western and southern parts of Northwest Siberia experienced more pronounced warming than did the eastern part. Climatic averages constructed from the gridded data set indicate a temperature increase in the Yamal Peninsula of 1.6–2.1 °C. The Tazovskiy and Gydan Peninsulas experienced an increase of 1.4–1.6 °C. Continental parts of the study area showed a 1.5–2.0 °C increase (Fig. 6, part a). Such a pronounced increase in air temperature is higher than that used by Khrustalev (2000) for Yakutsk, so substantial losses in bearing capacity could be expected. Corresponding changes in TTOP calculated by the model are smaller, because of the insulative effects of above-ground cover and attenuation of the climatic signal with depth, The regional increase of TTOP is 1.38 ± 0.13 °C. The largest increases are found just north of the treeline in the west and to the south of treeline in the east of the study area. This corresponds to the presence of peatlands, which offset climate warming. The increase of TTOP in Yamal and Tazovskiy is 1.2–1.5 °C, while in Gydan it is 1.0–1.4 °C (Fig. 6, part b). The estimated increase in TTOP in the continental part of Northwest Siberia is from 1.1 to 1.7 °C. The

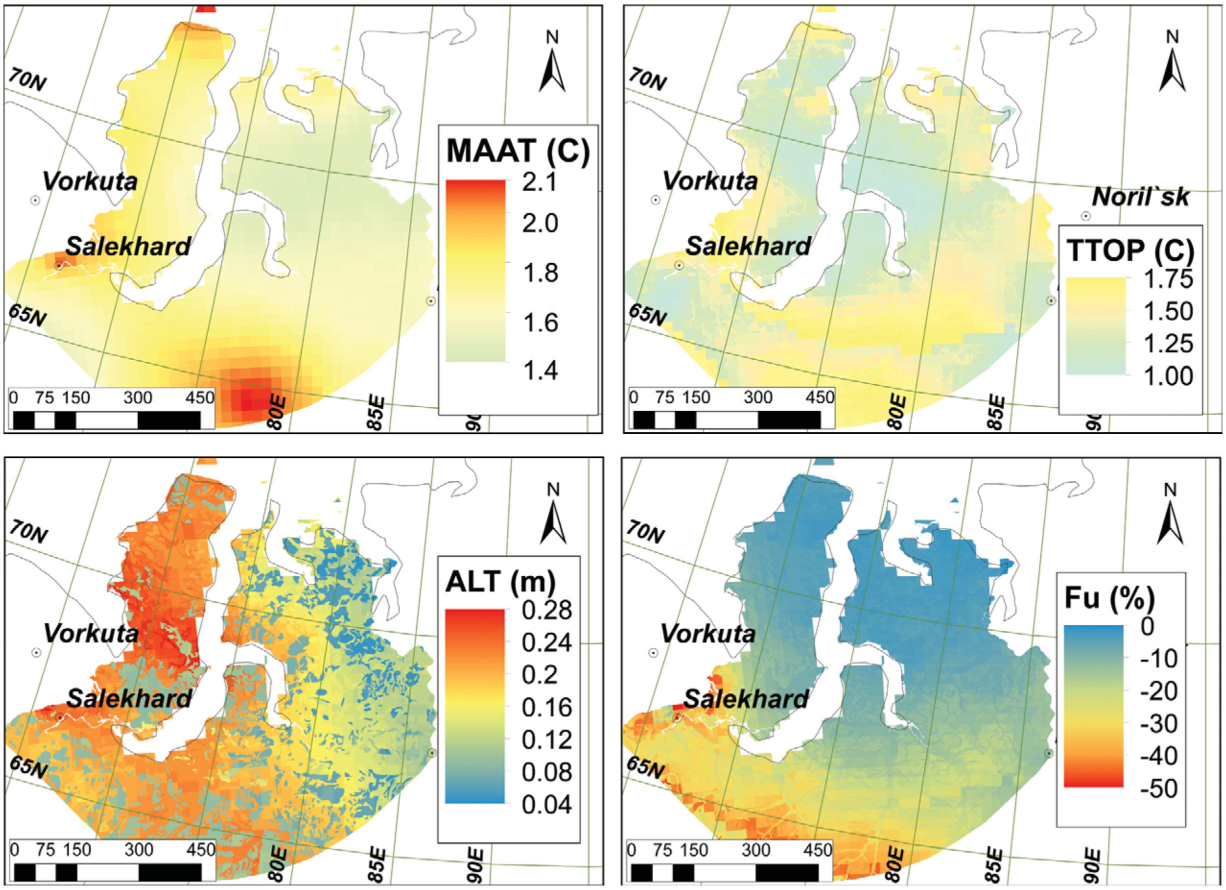

FIGURE 6. Regional changes in mean annual air temperature (MAAT), mean annual ground temperature at a permafrost top (TTOP), active-layer thickness (ALT), and bearing capacity (F_u) from 1960s to 2000s.

much higher level of landscape diversity, particularly the combination of peatlands and the presence of ground with high ice content to the south of treeline creates higher variability in the reaction of both TTOP and ALT to climate change.

ALT increased throughout the region. Regional changes of ALT between the 2000s and the 1960s are 0.16 ± 0.06 m and do not exceed 0.25 m. These changes, expressed as percentages, correspond to a 18.6 ± 8.9% increase in regional ALT. The highest percentage changes, on the order of 30–45%, are concentrated in northern and central Yamal, while the rest of the study area experiences a 10–15% increase (Fig. 6, part c). Within similar climatic conditions, sandy locations experienced the largest increases in ALT, while the smallest increases are attributed to peatlands.

Over the same period, bearing capacity decreased from 8 to 65% over the 555,000 km^2 of the study area (Fig. 6, part d). The regional decrease in bearing capacity for the entire study area is 29 ± 14%. The smallest decrease is seen in the northern part of the Yamal and Gydan Peninsulas, but the decrease gradually becomes more pronounced toward the south. Decreases of bearing capacity in the Arctic tundra zone are about 10–15%, in northern tundra 15–20%, and in southern tundra 20–25%. Increasing complexity of environmental conditions south of the forest line creates highly variable conditions in the bearing capacity fields. Forest-tundra areas show decreases of 25–40%, with more pronounced decreases in the western part. Substantial losses of bearing capacity are found to the south of treeline, where the majority of the area, with the exception of river valleys, is underlain by soil with high ice content. High ice content, in conjunction with increased TTOP results in decreases of 40–55% in the western half of the forest-tundra and taiga zones. Locations near Salekhard experienced decreases of 40–55%, while in the vicinity of Nadym it is 40–50%, and 30–40% around Pangody and Noviy Urengoy. Smaller decreases are found in the eastern part of the study area and along the Yenisey River, where the cities of Igarka and Dudinka experienced a decrease of about 15–20%.

The difference between air temperature obtained from weather stations located within the settlements and gridded data sets creates slight differences between estimates of bearing capacity. The estimates produced by the University of Delaware data set are, in general, slightly higher than those produced using weather stations.

TECHNOGENIC AND SOCIO-ECONOMIC FACTORS

Although our results demonstrate the adverse effects of climatic warming on the bearing capacity of foundations, technogenic factors, such as disturbance and lack of maintenance, can result in changes in the ground thermal regime far exceeding those produced by climatic forcing. For example, the socio-economic crisis that occurred after the collapse of the Soviet Union resulted in reduced monitoring of construction in many cities on permafrost during the early 1990s. In some cases, undetected leaks in sewage and water pipes resulted in rapid warming and chemical contamination of permafrost below the foundations. Increases in permafrost temperature and ground salinity and the resulting decrease in the soil's ability to support foundations resulted in serious deformation of many structures (Grebenets, 2003). In some cases the deformation was catastrophic, leading to collapse of entire structures. Permafrost monitoring in Noril'sk indicates that the number of leaks in building basements increased by a factor of 15–20 in the 1990s, compared to the 1970s. The major cause of building deformation (more than 60% of occurrences) became the loss of bearing capacity of frozen ground due to unpredictable rates of warming and thawing caused by prolonged leaks of pipes in basements (Khrustalev, 2000). A recent study conducted in Yakutsk (Alekseeva et al., 2007) concluded that the main reasons for decreasing foundation strength in Yakutsk were errors in planning and construction, rather than increased air temperature. Together with waterlogging and chemical contamination of groundwater, these errors resulted in catastrophic situations in residential districts. More than 20 cases of building failures have been reported since the 1970s. Degradation of permafrost in Noril'sk has led to deformation of 250 buildings, 35 of which are awaiting demolition. Currently, more than 30% of the structures in Noril'sk are affected by a decrease in permafrost-bearing capacity (Grebenets and Ukhova, 2008).

It can be difficult to discern between local anthropogenic and broader environmental causes (Nelson, 2003), which together have created conditions in which the percentage of structures experiencing deformation is astonishing in some settlements. Whether caused by climatic or technogenic factors, permafrost temperature increases are accompanied by increases in unfrozen water content and decreasing cohesion of soil particles, resulting in substantial loss of strength in the permafrost.

Summary and Conclusions

A GIS-based landscape approach was used to apply the combined model at regional scales, depicting changes in temperature at the top of permafrost, active-layer thickness, and bearing capacity in Northwest Siberia and the North Slope of Alaska. Results indicate that the active layer reacts more slowly to observed climate changes than does the temperature at the top of the permafrost. Increases in permafrost temperature, resulting in a corresponding decrease in bearing capacity, have occurred in most parts of the two study regions and are expected to continue. This raises concerns about the stability of infrastructure on permafrost under projected climate change in the Arctic, and about the accompanying socio-economic consequences.

Calculated changes in bearing capacity for some of the major settlements on permafrost show that those foundations built according to the first (passive) principle in the 1960s and 1970s are most likely to experience deformation at Nadym and Salekhard, and problems are quite likely in Yakutsk, Anadyr, Chersky, and Novy Port. Generally, areas located in the southern part of the permafrost region (with TTOP higher than –5 °C) are likely to experience more pronounced decreases in bearing capacity under warming of the magnitude predicted by climatic models.

Foundation-bearing capacity is a complex parameter that links socio-economic factors with environmental and geological settings. Observed climate changes show that climatic averages, even at timescales of 10–30 years, do not necessarily correspond to the climatic ''normals'' of decades that follow. The typical lifespan of buildings is more than 50 years, so reference climatologies used prior to construction can be substantially out of date. Global warming, which is projected to be most rapid and pronounced in the high-latitude regions, may be exacerbated by urban heat-island effects and is likely to decrease bearing capacity through both increasing permafrost temperatures and active-layer thickening. This will increase the probability of serious deformation of buildings constructed using the passive method, especially those built according to outdated reference climate data. Deformation of pipelines and industrial plants (especially chemical and metallurgical) can lead to emission of pollutants and deterioration of ecological conditions. Widespread deformation of structures may require relocation of residents, which will have large socio-economic impacts, especially on native communities.

There is clear need to implement up-to-date knowledge about climatic variability into construction design in permafrost regions. The empirical model of bearing capacity shows that rough estimates of the variability of this parameter can be obtained by using publicly available meteorological data. The model can be used as a tool to estimate past changes in bearing capacity that have occurred since the time of construction, as well as future changes, if coupled with climate projections. Although there are numerous limitations to this model, it can be used at virtually any scale and facilitates depiction of locations where changes in bearing capacity can create hazardous conditions.

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