CLIMATE CHANGE AND STABILITY OF URBAN INFRASTRUCTURE IN RUSSIAN PERMAFROST REGIONS: PROGNOSTIC ASSESSMENT BASED ON GCM CLIMATE PROJECTIONS*

NIKOLAY I. SHIKLOMANOV, DMITRY A. STRELETSKIY, TIMOTHY B. SWALES and VASILY A. KOKOREV

ABSTRACT. One of the most significant climate change impacts on arctic urban landscapes is the warming and degradation of permafrost, which negatively affects the structural integrity of infrastructure. We estimate potential changes in stability of Russian urban infrastructure built on permafrost in response to the projected climatic changes provided by six preselected General Circulation Models (GCMs) participated in the most recent Climate Model Inter-comparison Project (CMIP5). The analysis was conducted for the entire extent of the Russian permafrost-affected area. According to our analysis a significant (at least 25%) climate-induced reduction in the urban infrastructure stability throughout the Russian permafrost region should be expected by the mid-21st century. However, the high uncertainty, resulting from the GCM-produced climate projections, prohibits definitive conclusion about the rate and magnitude of potential climate impacts on permafrost infrastructure. Results presented in this paper can serve as guidelines for developing adequate adaptation and mitigation strategy for Russian northern cities. *Keywords: Climate Change, Permafrost Infrastructure, Russian Arctic Cities.*

INTRODUCTION

Planned socio-economic development during the Soviet period promoted migration into the Arctic and work force consolidation in urbanized settlements to support mineral resources extraction and transportation industries. These policies have resulted in very high level of urbanization in the Soviet Arctic. Major urban centers were developed to support coal (e.g. Vorkuta), gas (e.g. Nadym, Salehard, Novyy Urengoi), oil (e.g. Surgut, Nefteyugansk), ore mining and smelting (e.g Norilsk) industries and Northern Sea Route and river transportation (e.g Igarka, Dudinka, Dickson, Pevek). Despite the mass migration from the northern regions during the 1990s, following the collapse of the Soviet Union and the diminishing government support, the Russian Arctic

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population remains predominantly urban. In five Russian administrative regions bordering the Arctic Ocean 66 to 82% (depending on region) of the total population lives in Soviet-era urban communities (Heleniak 2014). Although some towns and centers have experienced a drastic reduction in population, others have continued to grow due to either an increase in development of extraction industries or the migration from collapsing communities (Heleniak 2010).

The political, economic and demographic changes in the Russian Arctic over the second half of the 20th century have coincided with climatic changes. Since the 1980s the northern regions of Russia have experienced unprecedented climate-induced environmental changes (e.g. IPCC 2014; RosHYDROMET 2014). Changes in natural systems impact humans with direct, immediate implications for land use, the economy, subsistence, and social life. Although some impacts of Arctic climate changes can be economically beneficial (e.g. decrease in climate severity and associated heating costs, longer navigation season), other changes negatively affect the natural environment, traditional and nontraditional sectors of the economy, and socioeconomic regional conditions (e.g. Bartsch et al. 2010; Ford 2009; Larsen et al. 2008; Shikomanov and Streletskiy 2013).

One of the most significant impacts of climatic changes for Russian northern communities is associated with perennially frozen ground, or permafrost, which underlines approximately 66% of the Russian territory (Figure 1 A). The presence and dynamic nature of permafrost constitutes a distinctive engineering environment. The construction of buildings in permafrost regions is challenging and can lead to profound problems that reverberate into the social and economic spheres (e.g. Nelson et al. 2002; Nelson 2003). For example, heated structures, erected directly on the surface over ice-rich permafrost, increase the flow of heat to the subsurface and induce localized differential subsidence and settling. A common method for avoiding problems related to thaw settlement is to elevate building foundations by constructing them on wooden, metal, or concrete piles embedded in the underlying frozen substrate (Figure 1 B). Such “pile foundations” provide a layer of air, which effectively decouples the heat generated by the structure from the permafrost-affected ground. More than 75% of the buildings in Russian permafrost regions are constructed on pile foundations.

The ability of permafrost to support pile foundations is traditionally evaluated by assessing its bearing capacity, which is defined as the maximum stress or load that can be applied to a single pile frozen into the permafrost without its failure or settlement (Tsitovich 1975). The bearing capacity depends on the pile design as well as thermal regime and mechanical properties of the permafrost-affected ground. While mechanical properties of soils do not change significantly over the lifespan of the common infrastructure, the parameters determining the thermal state of permafrost (e.g. permafrost temperature, thickness of the annually-thawed or “*active*” layer) can be altered by changes in energy and water balances at the ground surface. A majority of such changes

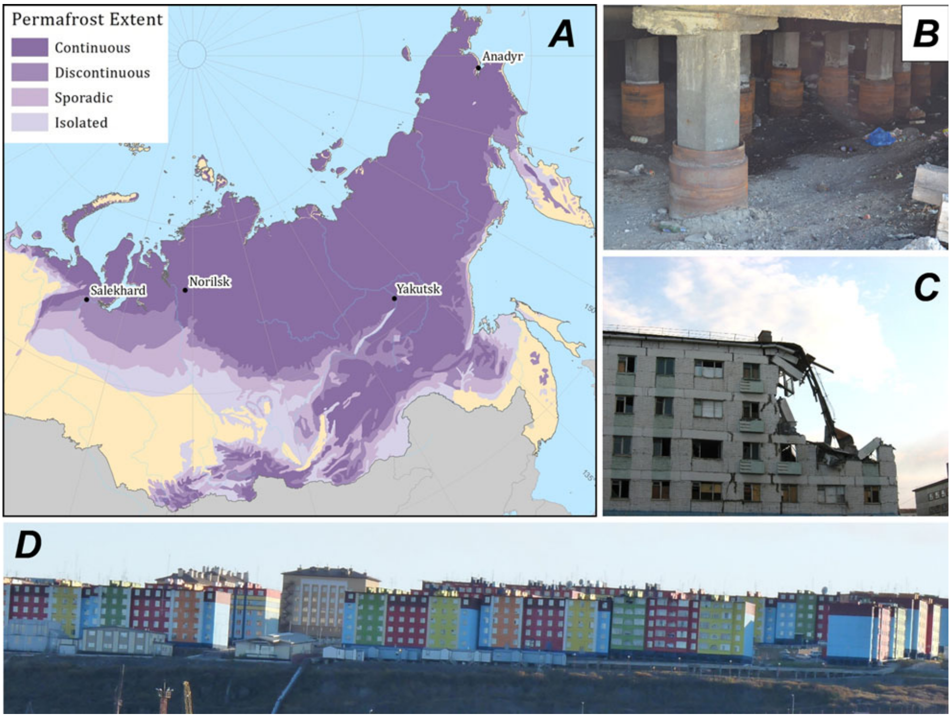

FIG. 1—(A) Permafrost distribution in Russia, based on Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2 (Brown et al., 2002) and locations of four cities discussed in this paper. Southern boundary of the discontinuous permafrost zone outlines the spatial domain of this study. (B) Standard 0.35m × 0.35m × 10m concrete piles supporting foundation of 1970s five-store residential building in Yakutsk. (C) Collapse of the five-store mid 1960s residential building in Norilsk attributable to the loss of foundation bearing capacity. (C) Panoramic view of the downtown city of Anadyr. Typical to all Russian arctic cities, urban infrastructure consists almost exclusively of 1960-1970s standard design five to nine story buildings on concrete pile foundations. (All photos by N. Shiklomanov)

are associated with anthropogenic modifications to the ground surface (e.g. removal of natural covers, artificial redistribution of snow, changes in water drainage). While anthropogenic factors have a pronounced effect on thermal and engineering properties of permafrost, such disturbances are anticipated and frequently accounted for in proper engineering designs.

Permafrost warming as a result of changing climatic conditions is well documented for many Russian regions (Romanovsky et al. 2010; Drozdov et al. 2015; Streletskiy et al. 2015). Climate- induced permafrost changes, however, were usually not fully considered in engineering practices. For example, Soviet (and Russian) Construction Norms and Regulations (e.g. CNR 1990) required the use of decadal climatic statistics (e.g. air temperature and precipitation) for assessing the state and potential variability of thermal permafrost parameters for bearing capacity estimates. Potential extremes and uncertainties in climatic conditions were accounted for during the engineering design stage by decreasing bearing capacity values obtained using decadal climatic normals by a so-called “safety coefficient.” While safety coefficients in North America range from 2.5 to 3, in Soviet Russia they were frequently as small as 1.05 and rarely exceeded 1.56 (Shur and Goering 2009). This means that for pile foundations with 1.05 safety coefficient, a decrease in bearing capacity by 5% can potentially cause deformation and possible collapse of the structure.

There are numerous reports indicating an increase in urban infrastructure damage throughout Russian permafrost regions over the last two decades (e.g. Anisimov et al. 2010; Grebenets, et al. 2012; Streletskiy et al. 2012a; Streletskiy et al. 2014; Khrustalev and Davidova 2007; Khrustalev et al. 2011 and Figure 1 C). In many instances it is difficult to differentiate between the effects of climate-induced permafrost changes and socioeconomic factors such as age, lack of maintenance, or design/construction flaws that may affect a structure on permafrost. However, while human-induced factors may or may not have contributed locally, climate change appears to be responsible for the broad patterns of the reported changes in infrastructure stability (Khrustalev et al. 2011; Streletskiy et al. 2012a; Anisimov and Streletskiy 2015). In this paper we use climate fields obtained from the last generation coupled General Circulation Models (GCMs) within the framework of permafrost engineering modeling to evaluate the potential impacts of the projected climate- changes on the stability of Russian urban infrastructure built on permafrost.

Methodology

Within the framework of this study we have utilized a quantitative approach for assessing climate change impacts on the stability of pile foundations (Konichev at al. 2011; Streletskiy et al. 2012 a, b). The approach is based on Russian methodology for evaluating bearing capacity, or the maximum stress, which can be exerted on the pile embedded into the permafrost. Two major types of stress constitute the bearing capacity: normal stress acts on the bottom of the pile in contact with the permafrost; and shear stress on the sides of the pile that come in contact with the frozen soil (Andersland and Ladanyi 2004). These stresses in turn depend on the cohesion of the frozen ground and the strength of the freezing bond between the pile and permafrost, which are functions of permafrost temperature. The Active-Layer Thickness (ALT) determines the surface area of the pile in contact with permafrost. As a result, the increase in permafrost temperature and/or thickness of the active layer will lead to decrease in shear and normal stresses and to reduction in bearing capacity. Formulations, obtained from Russian engineering literature (e.g. CNR 1990) are used to establish relations between parameters of the ground thermal regime (permafrost temperature, ALT) with stresses and bearing capacity.

Since piles can vary greatly in size, shape, and material depending on the type of infrastructure and engineering design, the selection of appropriate, site-specific parametrizations is required for assessing changes in bearing capacity for any particular structure and/or pile. This constitutes a local engineering problem, which is beyond the scope of this study that assesses and compares potential climate-induced changes in adfreeze bond strength of pile foundations with permafrost across the vast and diverse permafrost regions of Russia. To address this goal, we have used parametrizations for a generalized concrete 10m x 0.35m x 0.35m "standard pile." Illustration of these piles is provided in Figure 1 B. Such piles are most commonly used for standard-design 5-9 story buildings, which constitute the majority of urban housing in the Russian Arctic (Figure 1 C). The relative changes in bearing capacity of a standard pile can be calculated as a continuous geographical field and used as a proxy for geographical impact assessment of climate-induced permafrost changes on human infrastructure. The specific details on model formulation are provided in Streletskiy et al. (2012 a,b).

A spatial equilibrium permafrost model based on an analytical solution to the heat conduction problem in porous materials with phase change originally formulated by Kudryavtsev et al. (1974) was used to represent spatial and temporal changes in permafrost parameters (Mean Annual Ground Temperature (MAGT) and Active-Layer Thickness (ALT)). The model is driven by daily or monthly climate data (temperature, precipitation) and uses characteristics of surface (vegetation, snow) and subsurface (organic and mineral soil) properties to estimate permafrost MAGT and ALT. Numerous studies indicate that the model is capable of providing estimates consistent with observations and is applicable to different spatial scales (e.g. Anisimov et al. 1997; Shiklomanov and Nelson 1999; Sazonova and Romanovsky 2003; Streletskiy et al., 2012 c). Specific details on the latest equilibrium permafrost model formulations used in this study and its applicability for assessing GCM-projected climate-induced changes in permafrost conditions is provided in Streletskiy et al. (2012 c).

The accuracy of model is highly dependent on the correct representation of surface and subsurface properties (e.g. Shiklomanov et al. 2007). Due to the high uncertainty related to the characterization of localized conditions at broad geographic scale, considered in this study, all edaphic parameters were set to constant values for the entire area. We have used parametrizations, characteristic of sandy loam soils overlayed by a 0.05 m thick organic layer and 0.1 m thick live moss cover. While this approach does not realistically represent the entire permafrost area of Russia, it does allow us to isolate potential effects of climatic changes on the stability of urban infrastructure.

The engineering and permafrost modeling approach described above, was successfully applied for assessing changes in infrastructure stability attributable to climatic changes observed over 1960s-2000s periods at local (individual settlements on permafrost) and regional (West Siberia) scales (Streletskiy et al. 2012 a, b). In this study we are utilizing this methodology to forecast potential future changes in bearing capacity for the entirety of the Russian permafrost region (Figure 1A).

One of the major problems associated with prognostic climate impact studies is the large uncertainty in climatic projections. To address this problem, we have used projections provided by six preselected CMIP5 Global Circulation Models (GCMs): 1) CanESM2 (CanESM) - Canadian Earth Systems Model 2, 2) CSIRO-Mk-3.6 (CSIRO) - Commonwealth Scientific and Industrial Research Organization Mark 3.6, 3) HadGEM2-ES (HadGEM) Hadley Centre Global Environment Model Version 2 – Earth System, 4) GFDL-CM3 (GFDL) Geophysical Fluid Dynamics Laboratory Climate Model Version 3, 5) IPSL-CM5A-LR (IPSL) for Institute Pierre Simon Laplace – Climate Model 5A – Low Resolution, and 6) NorESM1-M (NorESM) Norwegian Earth System Model version 1-M. These models were selected by Anisimov and Kokarev (2013) from 48 CMIP5 GCM models participated in IPCC Fifth Assessment Report (IPCC 2014) based on their ability to simulate past climatic trends in Northern Eurasia. The selection approach compared GCM-produced regional trends of near-surface temperature and precipitation anomalies from the 1961-1990 climatic normal to observations over 1949-1960 and 1976-2005 periods (Anisimov and Kokarev, 2013). The models with the smallest deviations from observed trends in temperature and precipitation anomalies for the North Eurasian region were selected. Since each GCM has a different native resolution their outputs were rescaled to a common 1°Lat x 1°Long grid for comparative purposes. Only areas of Russia underlain by continuous and discontinuous permafrost were considered for the analysis since the use of pile foundations is unlikely in sporadic and island permafrost zones. The gridded fields of daily near-surface air temperature and precipitations produced by each of six GCMs over 1960-2100 period were used. The prognostic experiments from (2006-2100) ran under the RCP8.5 scenario, meaning that the radiative forcing at the top of the troposphere will increase by 8.5 W/m^2 by the year 2100. RCP8.5 represents the "worst case" climatic scenario (Riahi et al. 2011).

Following the Russian engineering practice of using decadal climate statistics for bearing capacity estimates (e.g. CNR 1990), GCM-produced climatic characteristics were averaged over five 10-year periods: past 1965-1975 (further referred to as 1970); present 1995-2005 (2000); near-future 2015-2025 (2020); mid-century 2045-2055 (2050); end-of-century 2090-2100 (2100). The permafrost and engineering models forced by six GCM-produced climates were used to evaluate the bearing capacities for each of the reference periods as well as their changes relative to 1970 and 2000 base periods. The 1970 climatic period was chosen since a majority of Russian urban infrastructure was built around that time. For example, according to the Russian Housing Authorities (gosjkh.ru) 63% of multifamily buildings in Norilsk, 53% in Yakutsk, and 61% in Anadyr' were constructed during 1960s and 1970s. To assess potential stability of these relatively old structures, the percentage of change in bearing capacity from 1970 to 2000, 1970 to 2020, and 1970 to 2050 reference periods were calculated. The 2100 time period was not used because it exceeds the 100 year lifespan of most Arctic infrastructure (e.g. Anisimov et al. 2010). The 2000 period represents recent infrastructure, developed as part of accelerated exploration of natural resources in Russian permafrost regions. To assess potential stability of modern structures the percentages of bearing capacity change from 2000 to 2020, 2000 to 2050, and 2000 to 2100 reference periods were used.

The results obtained using six GCM-produced climates were averaged to represent a model ensemble mean. Minimums and maximums in results were mapped to visualize the effect of uncertainty in climate projections.

Results and Discussions

PROJECTED CLIMATE CHANGES FOR THE RUSSIAN PERMAFROST REGIONS

Numerous studies have indicated that the Russian Arctic is warming at approximately 0.12°C per year rate which is significantly faster than the global average (e.g. Anisimov et al. 2013; IPCC 2014; RosHYDROMET 2014). The mean annual temperature anomaly reached 0.8°C in the last decade relative to the 1960-1990 reference period. According to the six-model ensemble selected for analysis, by the middle of the 21st century the mean annual air temperature increase relative to same base period is expected to reach +4.1°C in Salekhard and Norilsk, +3.7°C in Yakutsk and +4.0°C in Anadyr under the RCP8.5 scenario. Maximum changes are expected to occur in the fall and winter, with less warming during the summer and spring seasons.

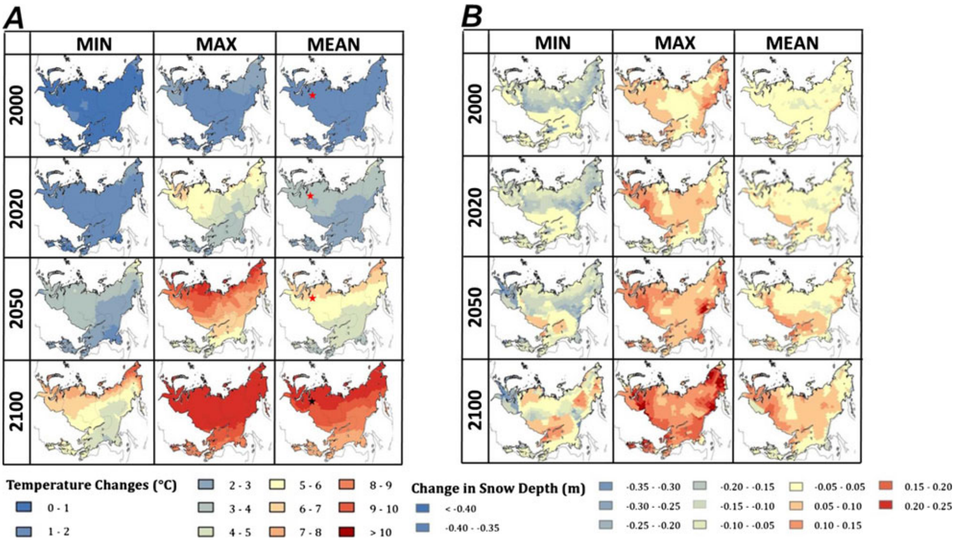

FIG. 2—Statistics (Min, Max, Mean) of Mean Annual Air Temperature (MAAT) (A) and Maximum Annual Snow Depth (MASD) (B) changes produced by an ensemble of six GCMs under RCP8.5 scenario. Changes are expressed as differences between averages for four decadal periods and the 1965-1975 period. Each year represents decadal average of MAAT and MASD for the following periods: 1970 for 1965 – 1975 period; 2000 for 1995-2005 period; 2020 for 2015-2025 period; 2050 for 2045-2055; 2100 for 2090-2100 period.

Figure 2 (A) shows statistics of mean annual near-surface air temperature anomalies from the 1965-1975 mean, produced by the ensemble of six GCM models for four decadal periods over Russian permafrost regions.

The increase in Mean Annual Air Temperature (MAAT) is evident across the region. The ensemble mean indicates the MAAT increase by 4 to 6 °C by 2050. The largest increases are expected in the northern part of the region. While general trends are similar between most (minimum) and least (maximum) conservative climate change estimates, the magnitude of change varies drastically.

The high uncertainty in observed and modeled precipitations over Siberia is well known (e.g., Anisimov and Ziltcova 2012; Groisman and Soja 2009; Groisman et al. 2013). Statistics (minimum, maximum, mean) of maximum annual snow depth anomalies from the 1965-1975 mean, produced by the ensemble of six GCM models for four decadal periods over Russian permafrost regions are shown in Figure 2 (B). Ensemble mean indicates an overall increasing snow accumulation trend over much of the region. However, the snow depth estimates derived from GCM-produced winter precipitation fields are very inconsistent in both, magnitude and direction of change as evident from maps portraying minimum and maximum snow depth estimates for each decadal period.

To illustrate the uncertainty in model-specific projections, Mean Annual Air Temperature (MAAT) and Maximum Annual Snow Depth (MASD) anomalies from 1970 reference period produced by each of six GCMs are plotted for the grid cell containing the city of Norilsk (Figure 3). When run in retrospective mode, the models produce relatively consistent results for air temperature (Figure 3A). The ensemble mean of MAAT for Norilsk shows 1.3°C temperature increase from 1970s to 2000s, which is in agreement with observations. HadGEM, IPSL, and NorESM were the best at reproducing the observed temperatures. However, the magnitude of projected changes varies drastically between models. GFDL consistently projects the highest temperature increase while CSIRO the lowest. The difference in projections provided by these two models is comparable with (and in some places exceeds) the increase in temperature projected by the mean of six models ensemble (Figure 3A). The estimates of snow depth vary greatly between individual models (Figure 3B). For the same grid cell the model-projected changes can be a significant decrease, no change, and a significant increase. For example for the grid cell representing Norilsk, HadGEM projects up to 0.25 m decrease in maximum snow depth, and IPSL up to 0.45 m increase, while GFDL and CSIRO models indicate no significant changes by the end of the 21st century (Figure 3 B).

EXPECTED PERMAFROST CHANGES

Since the ground thermal regime is highly dependent on atmospheric temperature and thickness of snow cover, the inconsistencies in GCM-produced climate

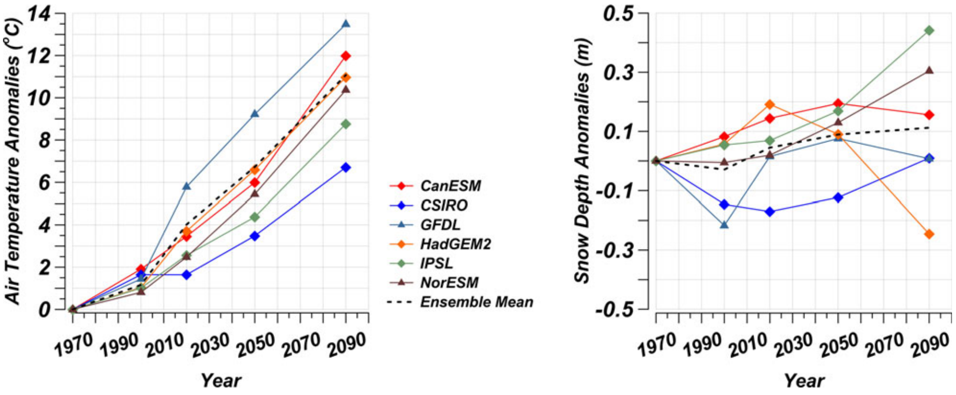

FIG. 3—GCM-specific projections of Mean Annual Air Temperature (MAAT) (A) and Maximum Annual Snow Depth (MASD) (B) change from 1965-1970 reference period for the model grid cell containing the city of Norilsk, indicated by a star in Figure 2 (A). In both graphs years on Y axis represent decadal periods used for calculations.

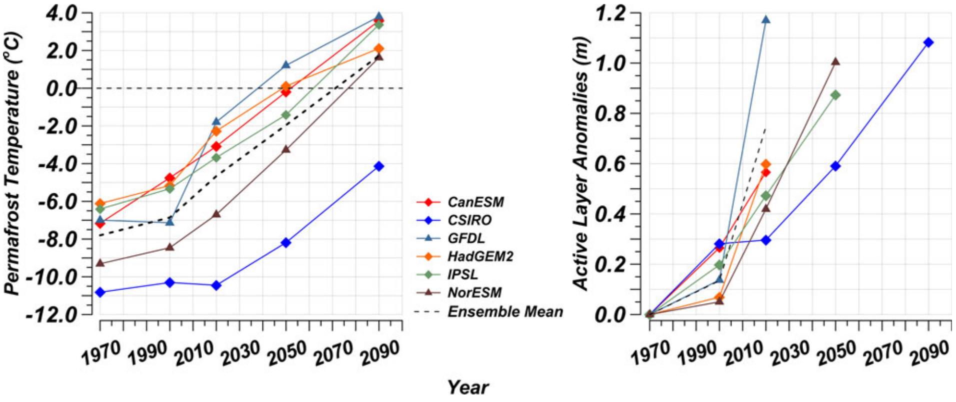

FIG. 4—(A) Permafrost temperatures estimated using climates produced by six GCMs for the model grid cell containing the city of Norilsk. (B) Active-Layer thickness anomalies relative to 1965-1975 period estimated using climates produced by six GCMs for the model grid cell containing the city of Norilsk. In both graphs years on Y axis represent decadal periods used for calculations.

fields lead to high uncertainties in projected change of permafrost parameters: Mean Annual Ground Temperature (MAGT) and the Active-Layer Thickness (ALT).

To illustrate such uncertainties Figure 4 provides estimates of MAGT (Figure 4 A) and ALT (Figure 4 B) changes relative to the 1970 reference period produced by the permafrost model forced by climatic projections from six GCM models for the grid cell containing the city of Norilsk. Observational evidence indicates that the permafrost temperature measured at 10 m depth in Norilsk has changed from -7 to -0.5°C range, depending on local conditions, prior to major construction in the mid-1960s, to -2.5 to 0.5°C in 2000s (Grebenetz et al. 2012). However, these observations were conducted within the city limits where permafrost is greatly impacted by anthropogenic influences. The lower model-produced estimates of permafrost temperature are representative of highly generalized natural conditions (Figure 4 A). This also explains the smaller rate of change between 1970 and 2000 periods produced by model ensemble compared to observations. Forcing the permafrost model by GFDL climate projection produces a reduction in permafrost temperature by 2000s. The ensemble mean indicates that the permafrost temperature will reach 0°C during the second half of the 21st century.

Observational active layer data are available for 2005-2013 from the Circumpolar Active Layer Monitoring (CALM) site R32 located in the vicinity of Norilsk in an undisturbed typical tundra landscape. The mean ALT over the observation period was 0.92 m (0.81 - 1.03 m). The permafrost model forced by ensemble of six GCM climate scenarios resulted in average 2000s ALT of 1.00 m which agrees well with the observations. Analysis of model-produced changes indicate an average of 0.13 m ALT increase from 1970s to 2000s and an additional 0.4 m increase by 2020 (Figure 4 b). Projected changes in permafrost temperature vary greatly between models. The GFDL climate model produces the highest rate of warming and CSIRO the lowest.

Analysis of model produced projection of permafrost temperature and the active layer for the model grid cell containing Norilsk indicate that climates produced by three GCMs (GFDL, HadGEM2, CanESM) result in the development of a residual thaw layer above the permafrost by the year 2050. The remaining three models project a 0.8 m average increase in ALT by the year 2050 relative to 1970. All models, except CSIRO, estimate near-surface permafrost degradation by the end of the century. According to CSIRO, low temperature permafrost will persist throughout the century.

EXPECTED CHANGES IN BEARING CAPACITY

Permafrost parameters estimated using climate from six GSM were used within the framework of the engineering model to assess the relative changes in bearing capacity and the ability of the frozen ground to support structures. Figure 5 shows statistics of relative (expressed in percentage) changes in bearing capacity from 1965-1975 and 1995-2005 periods estimated using climate projections produced by the ensemble of six GCM models.

Results presented in Figure 5 illustrate the uncertainty related to climate projections for climate-change impact assessments. According to conservative estimates, represented by maps of minimum change in Figure 5, the climate-induced decrease in bearing capacity will not exceed 25% by mid-21st century throughout the continuous permafrost zone. The conservative projection implies that even old 1970s structures have potential to withstand climate-induced permafrost changes if engineered with safety factors above 25%.

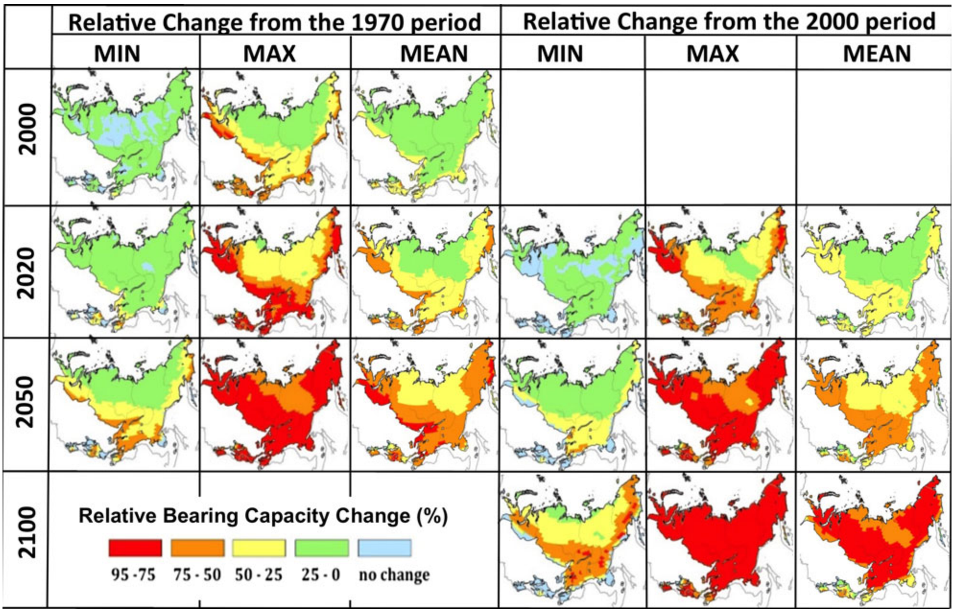

FIG. 5—Statistics of relative (expressed in %) changes in bearing capacity from 1965-1975 (1970) and 1995-2005 (2000) to decadal periods of 2000, 2020 (2015-2025), 2050 (2045-2055) and 2010 (2090-2100) estimated using climate projections produced by the ensemble of six GCM models. Changes relative to1970 period represent conditions faced by urban infrastructure built during the Soviet construction boom of the 1960s and 1970s. Changes relative to 2000 represent modern infrastructure.

Alternatively, the use of most extreme climate projections (maps of maximum change) produce 75-95% reduction in bearing capacity for modern (2000s) infrastructure throughout permafrost regions by 2050. Regardless of the climate projection the most significant reduction in bearing capacity is expected in discontinuous and southern fringes of continuous permafrost zones. This is especially true for the north-western portion of the Russian permafrost region. This area contains a large portion of Russian hydrocarbon reserves and since the 1980s has been a subject of increased urbanization and industrial development. A climate-induced decrease in infrastructure stability can potentially significantly impact approximately 350,000 people living in that region.

Four cities, representative of human development in the Russian permafrost regions, were considered to illustrate variability in potential stability of urban infrastructure resulted from uncertainty in climate projections: Salekhard, Norilsk, Yakutsk, and Anadyr (Figure 1). Salekhard (pop 40,000), located in Yamal-Nenets Autonomous Okrug (YNAO), is the administrative center of the largest West Siberian oil and gas region. Norilsk (pop. 177,000), in the North of Central Siberia, is one of the largest Arctic cities. Yakutsk (pop 200,000) is the capital of the East Siberian Sakha-Yakutia republic. Anadyr (pop 10,000) is

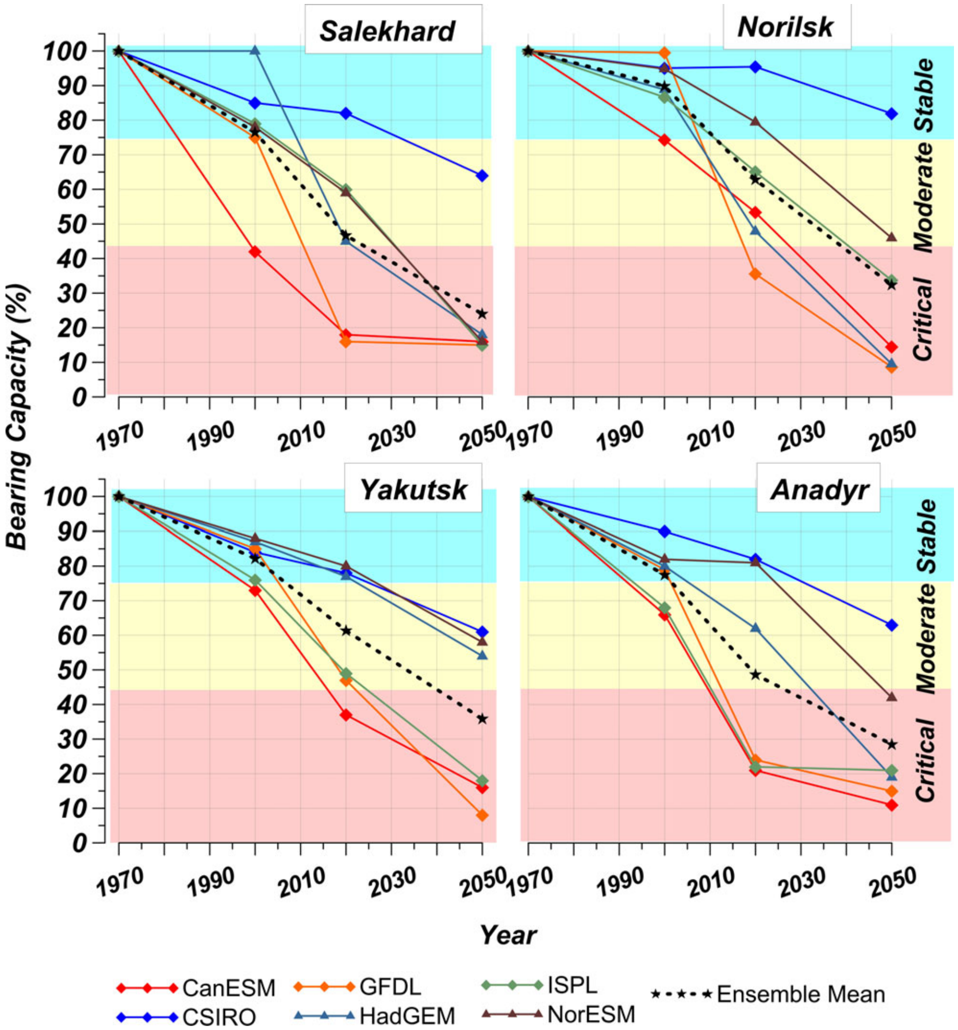

FIG. 6—Bearing capacity of standard pile foundation in percentages relative to 1965-1975 reference period estimated using climates, produced by six GCMs for the model grid cells containing for Russian Cities: Salekhard, Norilsk, Yakutsk, and Anadyr. Years on Y axis represent decadal periods used for calculations.

the administrative center of Chukotka Autonomous Region, on the coast of the Bering Sea. Model grid cells containing each city were extracted for analysis.

Figure 6 shows changes in bearing capacity relative to the 1970 period for model grid cells containing each city obtained using climate projections produced by six GCMs. Bearing capacity changes below 25% are considered to be within the range of changes anticipated by engineering design and, as such, do not significantly undermine stability of structures. On the other hand, bearing capacity changes of more than 55 % exceed the safety factors engineered into standard-design Soviet pile foundation (Shur and Goering 2009), potentially leading to critical deformation of structures. Changes within the 25%-55% range are considered to be moderate.

Estimates, obtained using average of six GCM-produced climate projections, indicate a progressive climate-induced reduction in bearing capacity of standard foundations for all four cities. The ensemble mean changes from the 1970s to 2000s periods, presented in Figure 6, are consistent with estimates obtained using similar approach driven by climate data observed at weather stations (Streletskiy et al. 2012a, b). On average, the fastest changes are projected for Salekhard and Anadyr. There the bearing capacity have potential to reach critical levels by mid 2020s. In Yakutsk and Norilsk the projected climate-induced decrease in bearing capacity will exceed 55% around the 2040s.

The use of individual GCM climate projections, however, results in high diversity in estimates of bearing capacity change. For all four cities, the most conservative climate-induced changes in bearing capacity are obtained using CSIRO climate. The largest changes are produced using Can ESM and GFDL climates. The range between high and low estimates of bearing capacity change can be significant. For example, for the city of Norilsk, the projected climate-induced reduction in bearing capacity between 1970 and 2050 reference periods is expected to be 18% when utilizing CSIRO climate projection versus 92% change projected by GFDL climate. In other words, CSIRO projects stability of 1970s Norilsk infrastructure through the first half of the 21st century, while estimates produced using GFDL climate indicate significant deformations of modern (2000s) structures by 2020s.

Effect of Non-Climatic Factors on Urban Infrastructure in Russian Permafrost Regions

Our assessment demonstrates the potential adverse effects of projected climatic changes on the bearing capacity of foundations and, as a result, on stability of infrastructure. However, the results presented in this study are not suitable for deriving definitive conclusion at the local scale. To isolate climatic impacts from other factors contributing to the stability of urban infrastructure our modeling approach relates climate-induced permafrost changes, characteristic of generalized undisturbed natural conditions, to bearing capacity of pile foundations used throughout the Russian permafrost regions for standard-design buildings. In many instances, such an approach can lead to more conservative results since changes in the ground thermal regime of urban environments can greatly exceed those of natural landscapes due to a range of anthropogenic stressors related to the construction and operation of the city. For example, the construction and maintenance of roads and utility lines, the removal and redistribution of snow and vegetation, and/or the additional heat generated by industrial and residential facilities can all lead to the significant modification of both mechanical and thermal properties of the frozen ground, which, as a rule, negatively affect the bearing capacity of foundations (Grebenets 2003; Grebenets et al. 2012). Even urban and industrial pollution can greatly effect infrastructure stability through soil salinization and related depression of the freezing point and intensification of chemical weathering of concrete foundation piles (Grebenets 1998; Grebenets et al. 2001). In many urban centers, anthropogenic disturbance led to pronounced permafrost warming and/or degradation beyond those explainable by observed climatic changes (e.g. Khrustalev et al. 2000; Grebenets and Sadowski 1993; Grebenets and Ukhova 2008; Alekseeva et al. 2007).

The socio-economic crisis that occurred after the collapse of the Soviet Union in 1990s has greatly affected the heavily-subsidized northern cities. Significant reduction in construction and maintenance of infrastructure, abandonment of standardized permafrost monitoring, and the outmigration of labor force have also contributed to negative anthropogenic impacts on urban permafrost. For example, undetected sewage and water leaks, reduction in centralized snow removal, and violation of construction codes contributed to further warming of permafrost below the foundations during 1990s in Norilsk resulting in serious deformation of many structures (Grebenets and Kerimov 2001). In Yakutsk, the main reason for accelerated decrease in foundation strength was attributed to errors in planning, construction, and maintenance of city infrastructure rather than climatic changes (Alekseeva et al. 2007). The analysis conducted by Khrustalev et al. (2000) has identified the lack of adequate monitoring and maintenance of leaking utility pipes as a major cause of bearing capacity loss resulting in significant building deformations throughout the Russian permafrost region.

Although anthropogenic causes contribute greatly to decrease in stability of urban infrastructure throughout Russian permafrost regions, the significance of climate-induced changes was demonstrated in several studies (e.g. Anisimov et al. 2010; Khrustalev and Davidova 2007; Shiklomanov and Streletskiy 2013; Smelev, 2010; Streletskiy et al. 2012 a,b;). For example, it was estimated that the 1.5°C increase in mean annual air temperature can potentially trigger deformation of almost all foundations in the city of Yakutsk (Khrustalev, 2000). The more recent assessments have attributed a 5-20% decrease in bearing capacity of permafrost foundations to observed climatic changes in number of Russian cities (Streletskiy et al. 2012b).

The study presented here demonstrates that projected climatic changes can potentially cause further significant reduction in the ability of frozen ground to support urban structures. We expect that technogenic and socio-economic factors will continue to have pronounced effect on infrastructure in Russian cities built on permafrost. Our results, however, indicate that the relative importance of climate-induced permafrost changes is likely to increase, resulting in additional stress for aging infrastructure of many Russian northern communities. Although a range of engineering solutions is available to mitigate negative impacts of permafrost changes on infrastructure, their cost is prohibitive for a city-wide applications in many economically vulnerable Russian municipalities.

The high uncertainty in rate and magnitude of potential impacts, resulted from GCM-produced climate projections and demonstrated in this paper, complicates the problem of developing adequate and cost effective adaptation and mitigation strategy further.

Summary and Conclusions

A comprehensive modeling approach was used in conjunction with six CMIP5 GCM-produced climate projections to assess potential changes in stability of urban infrastructure characteristic of Russian permafrost regions. The GCM ensemble mean projects a MAAT increase of 4 to 6 °C by 2050 over permafrost regions of Russia. The largest warming is expected in the northern part of the region possibly due to an Arctic-amplification, which is driven, in part, by sea ice reductions. Although increasing air temperature trends are evident from all projections, the rate, magnitude and spatial pattern of temperature changes ranges greatly between model-specific estimates. The GCM-produced precipitation fields are inconsistent in both, magnitude and direction of change. Projected climate change will promote an increase of permafrost temperature, a thickening of the active layer, and a decrease in bearing capacity of the frozen ground. This can potentially lead to deformation and collapse of structures. However, inconstancies in climatic projections lead to the large uncertainty in rate and magnitude of bearing capacity change. The most conservative estimates project a climate-induced decrease in bearing capacity of less than 25% by mid-21st century throughout the continuous permafrost zone. Such change should not significantly affect well-engineered structures. On the other hand, the use of the maximum from the model ensemble results in 75-95% reduction in bearing capacity throughout the permafrost region by 2050. This can have a devastating effect on cities built on permafrost. According to all GCM-derived climate projection, the most significant reduction in bearing capacity is expected in discontinuous and southern fringes of continuous permafrost zones.

For the four major Russian cities, considered for the analysis, our estimates, obtained using an average of climate-models runs, indicate a progressive climate-induced reduction in bearing capacity of standard foundations. On average, the fastest changes are projected for Salekhard and Anadyr. There the bearing capacity has potential to decrease to critical levels by mid 2020s. In Yakutsk and Norilsk the critical climate-induced decrease in bearing capacity is expected around 2040s. High uncertainty in climatic projections, however, does not allow definitive conclusion about the rate and magnitude of bearing capacity change for any of the cities used in this study.

It should be noted, that city-specific results of this study are presented for illustrative purpose. The very course spatial resolution of the current General Circulation Models precludes detailed analysis at the local scale. Spatial downscaling of GCM climate projections and detailed characterization of surface and subsurface conditions are required for assessing climate-induce permafrost changes for individual settlements. The modeling approach used in this study is developed to isolate potential climate effects on stability of urban infrastructure. As such it is not suitable for specific engineering and/or local scale application where site-specific conditions and anthropogenic factor can greatly affect stability of individual buildings. However, our analysis demonstrates that climate-induced permafrost changes can potentially undermine the structural stability of foundations indicating a clear need for adopting construction norms and regulations for permafrost regions that account for projected climate changes. The results presented in this paper can contribute to the development of new construction norms and adequate adaptation and mitigation strategies for Russian northern cities.

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