



## CHAPTER NINE

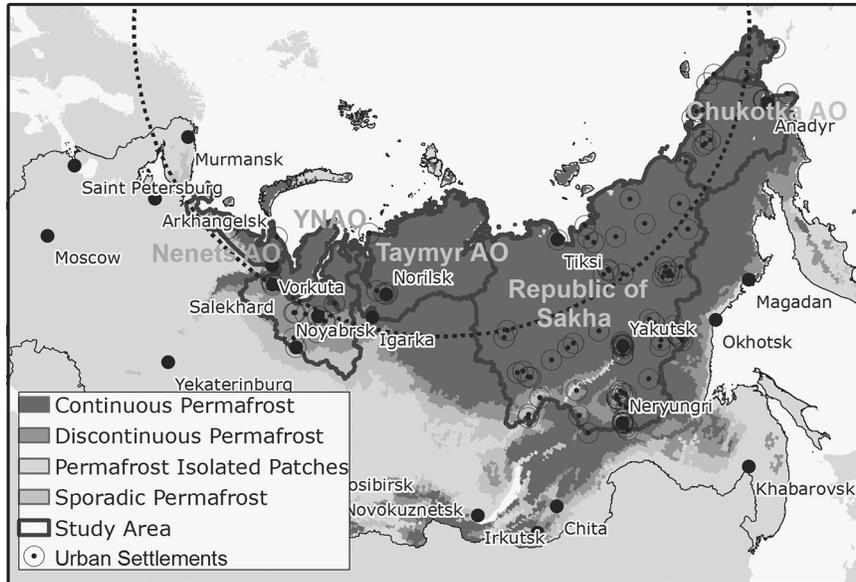
# Russian Arctic Cities through the Prism of Permafrost

*Dmitry Streletskiy and Nikolay Shiklomanov*

### Introduction

While the Arctic regions are generally sparsely populated, the population of the Russian Arctic is relatively large.<sup>1</sup> Urbanization in most of the Russian Arctic regions is higher than overall in Russia with the majority of the population concentrated in settlements with a distinct urban fabric (Rosstat 2014; Map 9.1). While there are numerous small towns scattered throughout the Russian Arctic, substantial populations are concentrated in large urban centers such as Vorkuta, Salekhard, Nadym, Novy Urengoy, Norilsk, Magadan, and Yakutsk. While high urbanization numbers are characteristic of the mainly non-indigenous population, many peoples of the North are integrated into the urban areas as well (Rosstat 2014). Although only about 5 percent of the total Russian population resides in Arctic regions, their contribution to the country's economy is disproportionately large. Therefore, maintaining labor resources and infrastructure in the Arctic is one of the key requirements for the continued prosperity of Russia's resource-oriented economy.

Ongoing and projected climatic warming presents significant challenges in sustaining Arctic communities as most of them are built on permafrost. Permafrost, defined as any subsurface material that remains frozen for more than two consecutive years, is widespread in northern latitudes, and almost two-thirds of Russian territory is affected by this phenomenon (Zhang et al. 2008). Permafrost deter-



**Map 9.1.** | *Study Area and Location of Urban Settlements in Russia Relative to Permafrost Distribution*

mines many important environmental processes, and presents numerous challenges to human development in the Arctic.

Almost all types of human activities involve significant alteration of the natural ground covers, promoting warming and degradation of permafrost. In turn, the bearing capacity of permafrost decreases with its warming, causing the weakening of foundations and potential damage to, and possible failure of, buildings, pipelines, and transportation facilities (Streletskiy, Anisimov, and Vasiliev 2014). To address these challenges, engineers utilize a range of practices to construct and maintain infrastructure on permafrost, making it possible to develop large tracts of the Arctic.

Climate warming has the potential to further reduce soil bearing strength, increase soil permeability, and intensify the potential for the development of such cryogenic processes as differential thaw settlement and heave, destructive mass movements, and the development of thermokarst terrain (Shiklomanov and Nelson 2013). Each of these phenomena has the capacity to cause severe negative consequences for urban infrastructure in the high latitudes (Khrustalev and Davidova 2007; Anisimov and Streletskiy, 2015). The difficulty of relocating urban settlements requires developing an adaptive capacity to mitigate the detrimental, permafrost-related impacts of climatic changes.

Numerous buildings in Russian Arctic settlements have experienced substantial numbers of structural deformations (Kronic 2001; Grebenets, Streletskiy, and Shiklomanov 2012). In many cases, influences such as age, lack of maintenance, or design/construction flaws affect a structure. However, recent studies (Khrustalev and Davidova 2007; Khrustalev, Parmuzin, and Emelyanova 2011; Streletskiy, Shiklomanov, and Hateberg 2012; Anisimov and Streletskiy 2015; Streletskiy et al. 2015) indicate that ongoing changes in climatic conditions partially explain the intensified rate of structural deformations of buildings erected on permafrost. Transportation routes and facilities are also subject to danger (Kondratiev 2013). 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. Warmer air temperatures further limit the accessibility of remote regions due to winter road deterioration, as explained in Chapter 8 (Stephenson, Smith, and Agnew 2011).

As climate warming continues to evolve (for details consult Chapter 7), it may further intensify detrimental impacts on infrastructure throughout the permafrost regions, even under appropriate environmental management and engineering practices. Collapsing roads and buildings can have severe socioeconomic consequences, since supporting most of the existing infrastructure will require expensive mitigation strategies and the associated economic impacts may reach far beyond the Arctic (Whiteman, Hope, and Wadhams 2013). This chapter attempts to quantitatively evaluate climate and technogenic impacts facing large settlements and their residents in the Russian Arctic under rapidly changing climatic conditions.

### **Permafrost as an Integrative Component of Climate- and Human-Induced Change**

With permafrost occupying about a quarter of the Northern Hemisphere's land surface, Canada and Russia contain the most extensive areas of permafrost: approximately 50 percent and 65 percent of their territories, respectively. The thickness of permafrost varies from a few meters near its southern limit to several hundred meters in the high Arctic. The maximum reported thickness is more than 1.4 km in unglaciated parts of Siberia (Washburn 1980).

Even though permafrost is ground that remains below 0°C for more than two years, even in the coldest conditions there is an active layer in which heat flux creates a stratum of seasonal thawing and freezing.

At any given location, the active layer can be defined as the maximum depth of annual thaw penetration. The influence of atmospheric processes on ground thermal conditions is moderated by local hydrology and processes occurring in the boundary layer of vegetation, snow, and surface organic matter (Streletskiy, Shiklomanov, and Nelson 2012b). In addition to climatic changes, any natural and/or anthropogenic disturbances at the ground surface that upsets the delicate equilibrium between climatic and ground thermal regimes are likely to promote permafrost warming, an increase in seasonal thaw propagation, and possibly permafrost degradation (Streletskiy, Anisimov, and Vasiliev 2014). As such, observable changes in permafrost conditions can serve as an integrative indicator of climate- and human-induced environmental change.

At small geographical scales, the distribution of permafrost is classified primarily on the basis of its lateral continuity into continuous, discontinuous, and sporadic zones. Because permafrost is a climatologically determined phenomenon, the distribution of these zones is crudely correlated with climatic zones. Within each zone, the permafrost continuity and thickness are generally increasing in the northward direction, while permafrost temperature and the depth of annual thaw are decreasing. However, this broad zonal pattern is greatly mediated by topographic, microclimatic, surface, and subsurface conditions resulting in a high spatial heterogeneity in ground thermal conditions, even within a small area characterized by uniform climate (Streletskiy, Shiklomanov, and Nelson 2012b).

Many engineering problems related to permafrost construction are associated with the loss of soil bearing capacity and increased potential for the development of such cryogenic processes as differential thaw settlement and heave. These processes usually result from changes in the permafrost thermal regime due to the disturbance of the ground surface, heat propagation from structures, and/or climatic changes (Grebenets, Streletskiy, and Shiklomanov 2012). Soil bearing capacity in permafrost regions is an important problem associated with climate change, primarily because of its strong dependency on temperature. Frozen soil can experience a significant loss of strength when warmed. Frozen soils containing excess ice (ice-rich soils) can be susceptible to settlement and thermokarst development, which occurs when ice-rich soil thaws. The presence of ice in the ground can be attributed to several thermodynamic, geologic, and geomorphologic factors, resulting in uneven vertical and lateral distribution and great variability in its amount and properties (Shiklomanov and Nelson 2013).

Observed climatic warming has resulted in a permafrost temperature increase of 0.5–2°C over the last three decades in the Russian Arctic (Romanovsky et al. 2010). The southern permafrost boundary has retreated northward in the Northern European part of Russia (Oberman 2008). Thawing of ice-rich permafrost is also occurring along the southern fringes of the permafrost zone in West Siberia (Vasiliev, Leibman, and Moskalenko 2008). Previously stable areas of North-Western Yakutia have begun to show evidence of permafrost warming in recent years (Romanovsky et al. 2010). The increase in permafrost temperature has been accompanied by an increase of active layer thickness (ALT) in the majority of the regions, and is especially pronounced in the Russian European North (Shiklomanov, Streletskiy, and Nelson 2012; Romanovsky et al. 2015). Increasing active layer thickness is generally considered to be one of the most immediate reactions of permafrost to the warming climate.

The reported changes in permafrost and the active layer are exacerbated in areas of concentrated human activities, especially in large settlements. The development of previously undisturbed areas is commonly accompanied by the removal of vegetation, changes to surface and subsurface hydrology, redistribution of snow, and modification of the soil's thermal properties. These, in turn, upset the heat exchange balance between the atmosphere and the ground. The resulting technogenically modified complexes are characterized by a suite of permafrost-related processes that are often drastically different from those that were characteristic of the area prior to development (Grebenets, Streletskiy, and Shiklomanov 2012). As such, cities represent a nucleus of anthropogenic impacts on the fragile Arctic environment where climate-induced impacts on permafrost conditions are greatly amplified. The combined human and climate effects on frozen ground for any given settlement depends on numerous factors, including the climate and environmental conditions at the location of the settlement, its size and population density, planning, architectural and engineering practices, and history of development.

### **The Permafrost Conquest: Construction Practices and Legacies**

Russia has a long history of Arctic exploration, which led to the extensive development of its northern territories. For example, the city of Yakutsk, located in a zone of relatively cold, thick continuous perma-

frost, was founded in 1632. Many permafrost-related challenges arose during the construction of the Trans-Siberian Railway (1891–1916), substantial portions of which lie on permafrost (Shiklomanov 2005). Many engineering practices developed by trial and error during that period are summarized in the first permafrost engineering book titled *Permafrost and Construction upon It* (Bogdanov 1912). Historically, Siberian settlements were characterized by low population densities, marginal environmental impacts, and poor infrastructure since they consisted primarily of small wooden houses on traditional basement foundations. Inexpensive reconstruction or relocation of the light structures to a new location addressed the inevitable deformations that took place.

This situation began to change drastically just before and, especially, after World War II. The vulnerability of the European part of the country to military invasion and the discovery of major reserves of vital mineral resources promoted intensified industrial development in the permafrost-heavy North-Eastern regions. Stalin's decision to concentrate forced labor into gulag camps during the 1930s and 1940s gave him a reliable supply of manual labor to conquer the harsh permafrost environment. For example, prisoners built the first brick and concrete buildings in the city of Norilsk by digging through perennially frozen sediments to the solid bedrock and then building foundations using conventional construction practices. While this approach can erect stable structures, it is prohibitively expensive without low-cost prison labor and applicable only in areas with thin sedimentary layers.

The abolishment of the gulag system in 1953, postwar housing crisis, and development of the North-Eastern regions forced the Soviet Union to adopt construction techniques that were affordable and quick. In the late 1950s, Nikita Khrushchev started a new era of massive construction that relied on cheap, standardized, prefabricated panel buildings. More than 50 million people (or a quarter of the USSR population) moved to new apartments during the first decade of this program. Simultaneously, the Norilsk engineer Mikhail Kim developed piling foundations for permafrost construction, which effectively elevate buildings above the ground surface to avoid heat penetration into the ground and redistribute pressure between several piles to support a large structural load. This construction method also decreased the disturbance of permafrost during construction, as the pile diameter was relatively small compared to other types of foundations. The elevated first floor with a crawl basement was clearly advantageous, as the basement remains ventilated during the winter

while being shaded during the summer, preventing the permafrost from thawing.

The introduction of relatively cheap piling foundations effectively conquered permafrost and opened an entirely new chapter in the Soviet history of development in northern regions. The cheap, prefabricated building designs resulted in a construction boom and promoted urbanization throughout the Arctic.

As a result, urban architecture in the Russian Arctic mainly consists of a mixture of five- to nine-floor buildings made from prefabricated panel or standard-design brick. The majority of such structures on permafrost are built using piling foundations, known as the “Passive Principle” of permafrost construction (Shur and Goering 2009) or as “Principle One” in the Russian literature. This approach uses permafrost as the base for the building foundation, protecting it from warming and thawing during construction and the lifespan of the structure, which is engineered to last thirty to fifty years.

The ability of pile foundations to carry a building’s structural load depends on many factors, such as ground temperature, texture, density, salinity, ice content, and the presence of unfrozen water. In unfrozen coarse sediments (gravels and denser), soil strength is primarily a function of internal friction. In frozen soils, however, it is a function of ice bonding, allowing for much heavier loads compared to those in non-permafrost regions, as considerable bearing capacity can be gained by freezing pile sides into the surrounding permafrost (*adfreezing*). The shear stress per side unit of a pile is much lower compared to the normal stress at the bottom of a pile, but the much larger adfreezing area of the pile side relative to the bottom allows redistribution of up to 80 percent of the pile bearing capacity to its sides. Adfreezing strength is strongly dependent on the permafrost temperature along the piles, which consequently makes a foundation’s total bearing capacity highly dependent on permafrost temperatures, which in turn depend on the climate and insulating properties of ground covers, such as snow and vegetation. Temporal variability of air temperature and snow results in climate-induced changes in the load-bearing capacity of permafrost (Streletskiy, Shiklomanov, and Nelson 2012a). Russian Construction Norms and Regulations on Permafrost (CNR) (CNR 1990) recommend using standard climate statistics available at the time of construction to account for average climatic conditions and possible natural variability. Observed climate changes now, however, might exceed the climate variability engineered into piling foundations constructed during the Soviet era, which can potentially reduce the stability of structures.

## Quantifying Infrastructure Stability under Climate Change

Every structure requires an individual engineering approach; however, simple quantitative assessments of foundation stability are possible even at larger, regional scales. To assess changes in the potential stability of Arctic infrastructure, we have used the bearing capacity of the standard 0.35x0.35x10 m concrete foundation pile. Such an approach is frequently used in Russia for preliminary engineering assessments of large territories. This method allows avoiding uncertainties due to diversity of possible construction designs and practices, while focusing on changes in engineering properties of permafrost characteristics in response to climatic forcing. Foundation bearing capacity was calculated using parameterizations provided by the Construction Norms and Regulations (CNR 1990), which relate active layer thickness and permafrost temperature to stresses experienced by the pile foundation imbedded into the permafrost. Changes in permafrost parameters (for example, active layer thickness, permafrost temperature) were estimated using a spatially distributed model of permafrost-climate interactions (Streletskiy, Shiklomanov, and Nelson 2012b).

To evaluate changes in bearing capacity over large geographic areas, the model was developed with climatic inputs obtained from the National Center for Environmental Prediction (Kalnay et al. 1996). The climatic inputs consist of gridded datasets of daily temperatures and precipitation, scaled to 25 km<sup>2</sup> resolution. The assessments were focused on two reference periods: 1965–1975, and 1995–2005. The decadal periods were chosen to illuminate interannual variability in data and to focus on climatic changes rather than on weather oscillations of any particular year. The decade of 1965–1975 was chosen as a baseline period due to the extensive construction in the Russian Arctic at that time. It is assumed that structures were designed to withstand the climatic conditions of the period. The 1995–2005 period was selected to represent contemporary conditions, as at the time of analysis, the most recent climate data were available through 2005. Land surface data is composed of a uniform sand profile with low ice content, which is considered as the most favorable lithological conditions for construction. All the results presented in this chapter are in the form of relative change between the two selected periods.

Geographically, this analysis focuses on five Russian administrative regions bordering the Arctic Ocean and largely covered by permafrost: the Nenets Autonomous Okrug (AO), the Yamal-Nenets AO, the Taymyrsky Dolgano-Nenetsky District (formerly the Taymyr AO), the

Republic of Sakha (Yakutia), and the Chukotka AO. Collectively these regions comprise a significant portion of the Russian Arctic and its population.

To estimate the impacts of climate change on the population, population data were taken from the 2002 Russian Census as it centers on the 1995–2005 period (Rosstat 2014). Some regions experienced population change between the 2002 and 2010 censuses, which is discussed in the following section. However, it is important to note that the 2002 census population should be utilized, as representative of the selected climatic period.

### **Geography of Russian Arctic Urban Population**

A majority of the Russian Arctic population is concentrated in urban centers. While the proportion of the indigenous peoples of the North living in urban areas is less relative to non-indigenous groups, about 30 percent are urban (Rosstat 2014). City residents made up 73 percent of the total 1.85 million people living across the study area in 2001. Although the population in this area decreased to 1.62 million by 2010, the percent of urban population remained the same (Rosstat 2014). One hundred settlements across the five study region accounted for an urban population of 1.36 million people. One-third of the settlements had 2,000–10,000 people, about a fifth had a population of 10,000–50,000 people and six cities were above 50,000.

Sakha Republic had the highest number of settlements and largest population of the five administrative regions within the study area. The 73 settlements located within Sakha accounted for a population of 623,200 (by 2010, the population decreased by only one thousand). This is nearly 65 percent of the study area's total settlements and just under half of the total urban population.

With fourteen settlements, the Chukotka AO had the second greatest number of settlements, though these settlements tend to be much smaller. The urban population of Chukotka in 2001 was 46,000, or less than 5 percent of the study area's total. The largest settlement in Chukotka was Anadyr, with a population of 11,300. Even though Anadyr's population did not change, the number of urban settlements dropped nearly 50 percent by 2010 with only 32,300 people left in the urban settlements. The Yamal-Nenets AO was similar to Chukotka in number of settlements; however, its urban population was the second largest in the study area, accounting for nearly 30 percent of the total urban population with 386,600 people (the urban population

increased substantially by 2010 to 464,100). The Taymyrsky Dolgano-Nenetsky District (hereafter Taymyr) had five settlements, with a total population of 252,400. This is 5 percent of the study area's settlements and nearly 20 percent of the population. Geographically Taymyr includes settlements of the Taymyr District (24,000) and the Norilsk Urban Okrug, which are under the jurisdiction of Krasnoyarsk Krai. Dudinka, Talnakh, and Norilsk are the biggest settlements that are within the region's jurisdiction.

The Nenets AO had the fewest settlements and the smallest urban population, with three settlements accounting for 27,200 people (no change in 2010). The Nenets AO accounts for less than 5 percent of the study area's total settlements and urban population.

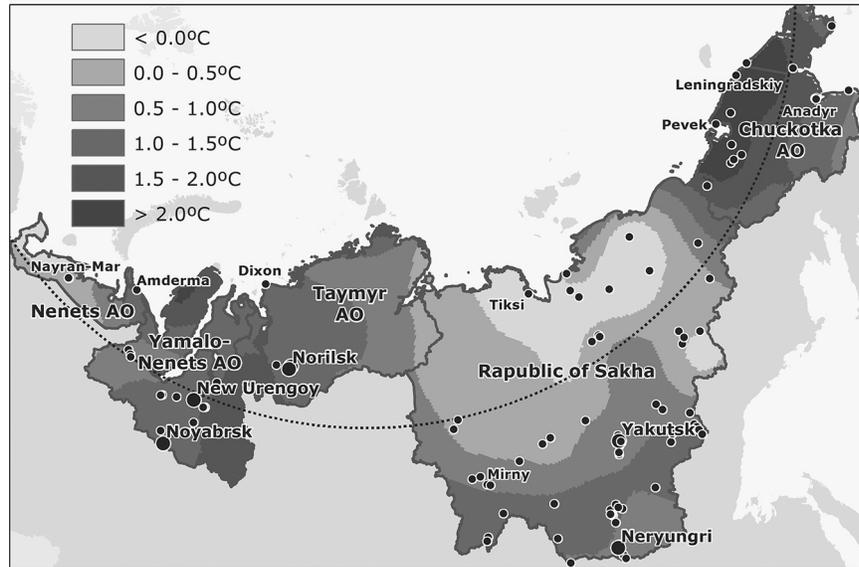
The two largest settlements of the study area were the cities of Yakutsk in the Sakha Republic and Norilsk in Taymyr. Other cities with populations above 50,000 included: Noyabrsk and Novy Urengoy in the Yamal-Nenets AO, Neryungri in Sakha, and Talnakh in Taymyr (Talnakh was recently merged into the Norilsk Industrial Okrug).

From 2001 to 2010, Chukotka AO lost almost 30 percent of its population, while Yamal-Nenets AO was able to grow significantly (see Chapter 4). Settlements in the Russian North remain highly concentrated. The indigenous population remained integrated into the urban settlements: 21 percent Nenets, 24 percent Chukchi, 38 percent Khanti and as many as 57 percent Mansi were urban, with a much higher percent of women relative to men (Rosstat 2014). Throughout the chapter, Norilsk, Yakutsk, Neryungri, Novy Urengoy, and Noyabrsk will be referenced as changes in infrastructure parameters in these places could pose consequences to a large number of people.

## **Effects of Climate Change on the Population**

Most of the study area experienced pronounced climate warming between the 1970s and 2000s time periods, with only a few areas showing no warming trend such as the western part of the Nenets AO and Northern Sakha. The mean annual air temperature across the region for the 2000s time period was  $-9.5^{\circ}\text{C}$ , up from  $-10.4^{\circ}\text{C}$  for the 1970s time period. A majority of settlements experienced temperature increases between  $0.5^{\circ}\text{C}$  and  $1.5^{\circ}\text{C}$  (Map 9.2). Only seven settlements, all located in Sakha (Yakutia), did not experience climate warming between the two periods.

Chukotka was the administrative region with the most pronounced warming, with over half of its area experiencing temperature increases



**Map 9.2.** | Changes in Mean Annual Air Temperature between the 1970s and 2000s

above 1.5°C. The northern part of Chukotka experienced the most significant increases, with temperatures rising more than 2°C. Of the 10 settlements to experience the greatest change between the two time periods, nine were within northern Chukotka. The highest change occurred in the settlement of Leningradskiy, a gold mining town of 760 people in 2002 (no permanent population remained by 2010), where the temperature increased by 4°C. The majority of the settlements experienced temperature increases above 2°C, including Pevek, Mys Schmidta, Bilibino, and Egvekinot. Cherskii (Sakha), which is relatively close to these settlements (directly across Chukotka's western border in Sakha), experienced a warming of 2°C. Together, these settlements accounted for a population of 27,000 in 2002. Other areas with considerable warming include parts of the Yamal Peninsula in the northern Yamalo-Nenets AO, with increases above 1.5°C. Large population centers present particular interest. Of the biggest cities, Norilsk has experienced the most significant change in temperature, 1.4°C. Mean annual air temperature in Novy Urengoy and Noyabrsk increased by 1.3°C. Neryungri and Yakutsk experienced 0.9°C and 0.8°C increase respectively.

While the primary trend has been a pronounced warming, some areas also exhibited no change or even a decrease in air temperatures.

Across the study area, temperatures decreased above the Arctic Circle in the western Nenets AO and northern Sakha, along with a small area in eastern Sakha. Only six settlements exhibited temperature decreases, all located in northern Sakha. The settlement with the most pronounced decrease between the 1970 and 2000 time periods was Tiksi with a decrease of almost  $0.5^{\circ}\text{C}$ . The remaining settlements were Severniy, Ust-Kuyga, Chokurdakh, Belaya Gora, and Deputatskiy. All six settlements had small populations, the largest of which is Tiksi, with a population of above 5,000. Together, these six settlements accounted for 18,000 people. Conversely, 79 settlements witnessed temperature increases above  $0.5^{\circ}\text{C}$  accounting for a population of 1.2 million people, demonstrating that for most settlements and the vast majority of the population of the Russian Far North, warming has been the primary climatic trend in recent history.

### **Effects of Climate Change on Infrastructure Stability**

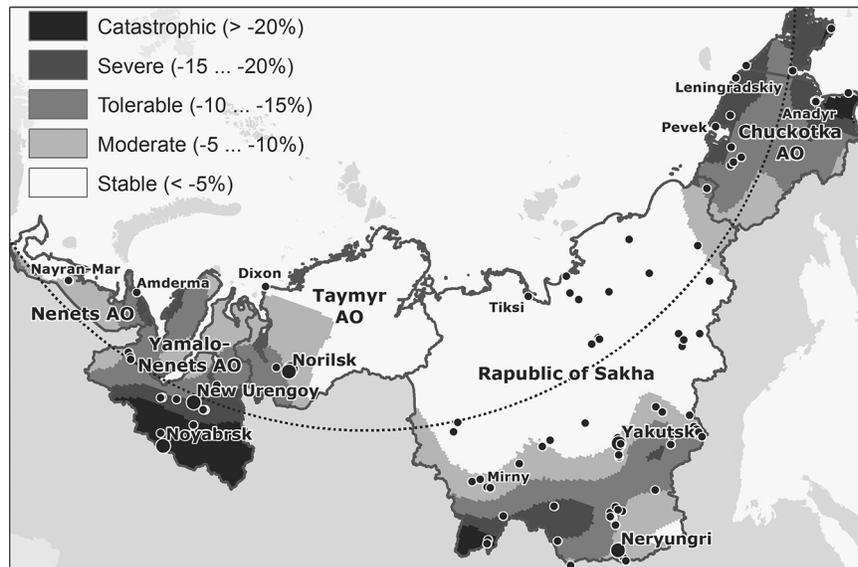
Though air temperatures are the main driver of change, warming temperatures alone do not translate uniformly to impacts on infrastructure and living conditions, as other bioclimatic indicators may intensify or offset the impacts of these changes. However, temperature change sets an important baseline for quantitative impact assessment across the region. Effective permafrost engineering designs aim to protect permafrost from warming through isolation during the summer and by providing heat exchange between the permafrost and atmosphere during the winter. With adequate maintenance, this exchange allows for relatively stable permafrost temperatures (while even occasionally resulting in temperature decreases). In the ideal case, the permafrost temperature beneath structures built using the passive method with an elevated first floor will approach the mean annual air temperature of the surrounding area.

Actual conditions, however, differ significantly from the ideal. A substantial number of reports on the deformation of structures built on permafrost, both in the scientific literature (Kronik 2001, ACIA 2005) and the public media, have prompted speculation that climate warming is at least partially responsible. While this chapter focuses on a broad geography, as site-specific studies are largely beyond the scope of the current work, it is important to note that the typical Soviet-era five story apartment building has on average 80 households totaling about 185 residents. Structural problems with only a few of these buildings can become a serious issue as hundreds of residents have to be re-

located. In many cases, the urban indigenous population has the fewest opportunities and smallest amount of economic resources to relocate.

Our results indicate that observed climate warming has the potential to decrease the bearing capacity of permafrost foundations built in the 1970s in the majority of settlements across all five study regions. Substantial decreases in potential foundation bearing capacity occurred in the regions of eastern Chukotka, southern parts of the Yamal-Nenets AO, and the Sakha Republic (Map 9.3).

The largest decreases in bearing capacity occurred in eastern Chukotka along the Pacific Ocean, southern Yamal-Nenets AO, and the southeastern tip of the Sakha Republic. In these areas, settlements saw a catastrophic drop in bearing capacity of more than 20 percent from the 1970s to the 2000s period. Settlements including Noyabrsk, Muravlenkovo, and Tarko-Sale in the Yamal-Nenets AO; Beringovskiy and Provideniya in Chukotka; and Vitim and Peleduy in Sakha were affected, totaling 166,000 people in 2002. Of these areas, most concerning are the three settlements in the Yamal-Nenets AO, which accounted for a population of 151,000. Loss of infrastructure stability in this region is particularly problematic, as the majority of the Russian oil and gas infrastructure is located in the Yamal-Nenets AO, as are the largest energy-producing urban settlements.



**Map 9.3.** | *Changes in Foundation Bearing Capacity between the 1970s and 2000s*

Areas least affected were 22 settlements considered stable, with a bearing capacity percent change of less than 5 percent. All except one (Dikson, in Taymyr) were located in northern or central Sakha. Of the four settlements that experienced increases in bearing capacity relative to the 1970 period, all were located in northern Sakha, including Severniy, Belaya Gora, Deputatskiy, and Ust-Kuyga.

The biggest cities with the largest decreases were Noyabrsk (28 percent) and Novy Urengoy (15 percent). Norilsk, Neryungri, and Yakutsk all experienced moderate changes, decreasing 10, 9, and 6 percent, respectively. According to our estimates, climate-induced decreases of bearing capacity of 15–20 percent occurred in Salekhard and Nadym, and smaller decreases of 5–10 percent occurred in Lensk and Cherskiy. Anadyr and Pevek experienced the most severe decreases, with more than 20 percent loss of bearing capacity.

While climate warming is a plausible cause for decreases in foundation bearing capacity, other technogenic factors, such as inadequate structural design or lack of proper maintenance, should also be considered. Undetected leaks in sewage and water pipes are well known to result in rapid warming and chemical contamination of permafrost below building foundations. The resulting decrease in the soil's ability to support foundations has resulted in serious deformation of many structures (Grebenets, Streletskiy, and Shiklomanov 2012). While the in-depth investigations that would be required to assess foundation deformation caused by technogenic factors are well beyond the scope of this study, our results clearly indicate that climate warming has a significant potential for undermining the structural stability of structures built on permafrost.

### **Role of Nonclimatic Factors on Infrastructure Stability**

A wide variety of foundation impacts are related to environmental effects of the built environment, most noticeably changes in conditions at the ground surface, such as those related to snow and vegetation. All settlements experience changes in radiation balance due to changes in their surface albedo, which in turn affect wind speed and direction, playing a role in snow redistribution. Moreover, even relatively small Arctic settlements can act as heat islands (Klene, Nelson, and Hinkel 2012; Konstantinov, Grishchenko, and Varentsov, 2015). Another problem is changes in snow albedo due to pollution in industrial centers of the Arctic. In the cities of Vorkuta and Norilsk snowmelt occurs a month earlier than in surrounding areas due to the

accumulation of dust particles from coal and metallurgy plants. Soil salinization and waterlogging is another problem facing some of the Russian Arctic cities built on permafrost, particularly those with developed mining and metallurgy industries; Norilsk and Vorkuta again fall into this category. Technogenic salinization is not only leading to decreases in the stability of infrastructure through increases in active layer thickness and temperature rises in soil, but also directly affects foundations through the corrosion of metal and concrete in the active layer. Another major problem is excess heat from numerous underground utility pipes, which slice frozen ground into relatively small strips, isolating patches that warm faster than otherwise larger frozen areas would (Grebenets, Streletskiy, and Shiklomanov 2012). In this section, we briefly outline the importance of changes in snow cover and vegetation conditions in urban areas. Readers interested in a detailed explanation of the diverse impacts of permafrost degradation can find them in related publications (Anisimov et al. 2010; Khrustalev, Parmuzin, and Emelyanova 2011; Shiklomanov and Nelson 2013; Streletskiy, Anisimov, and Vasiliev 2014).

In order to maintain accessibility to key urban services, such as roads, driveways, and parking lots, other areas are used as snow dumps—yards, parks, rivers, and lakes. Not surprisingly, a redistribution of snow in populated areas leads to changes in ground temperatures and may intensify some of the ongoing cryogenic processes. As a rule, areas with higher snow accumulation will have warmer ground temperatures, as more snow provides more thermal insulation in winter and areas with no snow will have colder ground temperatures. Consistently warmer ground temperatures and excessive water resulting from snowmelt may lead to permafrost degradation, melting of ground ice, associated ground subsidence, and thermokarst development. Consistently colder temperatures intensify cryogenic weathering, frost cracking, and frost heave.

For example, removal of snow from roads leads to an increase of cold flux in the ground during the cold period of the year, resulting in lower ground temperatures relative to natural settings. Observations in Norilsk have shown that in the areas used as snow dumps, the permafrost temperature is 2–3°C higher than under consistently cleared roads (Grebenets, Streletskiy, and Shiklomanov 2012). Colder permafrost temperatures along roadways alter surface runoff, since road pads act as frozen dams, leading to waterlogging along the roads during the warm season. While areas along the roads accumulate standing water in the summer, leading to thermokarst development in the long term, the roads themselves experience an intensified process

of frost cracking, differential frost heave, and subsidence, resulting in uneven road surfaces. These processes significantly limit the life span of the roads in the Arctic, requiring expensive maintenance and creating potentially dangerous driving conditions. Unfortunately, there are no effective extant methods to mitigate waterlogging along Arctic roads, so the monitoring of road beds is essential.

Similarly to snow, vegetation provides thermal insulation to the ground. Despite the fact that vegetation provides less ground insulation than snow, the influence of vegetation on the ground temperatures is complex, especially in high shrub and forest environments. Not only does it act as a thermal insulator between the atmosphere and the ground, but it can also play a substantial role in the redistribution of snow cover (Kudryavtsev et al. 1974). Snowmelt under forest canopies is different than in open environments, as the overlying canopy intercepts radiation and suppresses wind. As a result, melt rates are lower in forests than in equivalent open areas. Higher snow accumulation was found in areas of low shrubs, compared to those with tall shrubs and sites without vegetation. An important role in heat exchange at the surface in Arctic environments is attributed to moss cover as the presence of moss leads to a lower mean annual temperature protecting permafrost from thawing (Walker et al. 2003). Moss cover has been demonstrated to significantly reduce ground temperatures and thaw depth, demonstrating its importance to the overall ground temperature regime (Kade and Walker 2008).

The destruction of vegetation and moss cover in urban areas increases heat flow into the ground, leading to increases in active layer thickness and permafrost temperatures, thereby decreasing the stability of the structures built on permafrost. The removal of vegetation further intensifies erosion processes on slopes. Changes in vegetation extent can exceed the development area by several times, for example, dead taiga near Norilsk extends tens of kilometers from the city limits due to extensive pollution spreading from urban factories. The vegetation disturbance was found to exceed areas of gas production in West Siberia by 3–5 times (Garagulya et al. 1996). Technogenic waterlogging also has resulted in the deterioration of biodiversity in affected forests of the taiga zone.

## **Conclusions and Perspectives**

The Arctic urban population is at the frontier of climate change. Climate change is not uniform, but can be exacerbated in areas of con-

centrated human activities. The combination of technogenic impacts and warming climate can have severe socioeconomic consequences, especially in large population centers located on permafrost. Numerous studies documented that permafrost stores large amounts of carbon, however the impact of permafrost thaw on global climate system is relatively small, (Streletskiy, Anisimov, and Vasiliev 2014). At the same time, the impacts of climate and human-induced change on permafrost are a considerable threat to human development rather than a long-term concern and are largely neglected. One of the immediate impacts is the decrease in the ability of foundations built on permafrost to support buildings and structures, affecting a substantial portion of the population residing in the Arctic cities. Intensification of such processes as coastal erosion due to a longer ice-free period, waterlogging, and thermokarst development is likely to reshape tundra landscapes, with negative effects on accessibility and the functioning of northern communities. Therefore, a changing climate in the northern regions could profoundly affect the entire Russian economy as it depends heavily on the extraction and transportation of mineral resources from the Arctic. More detailed interdisciplinary studies, including integration of traditional knowledge, establishment of long-term monitoring of permafrost in urban areas, and comprehensive evaluation of the relative role of climatic and human-induced impacts on infrastructure on permafrost are required in order to develop sustainable strategies for Russia's Arctic cities.

**Dmitry Streletskiy** is Assistant Professor of Geography and International Affairs at the George Washington University.

**Nikolay Shiklomanov** is Associate Professor of Geography and International Affairs at the George Washington University.

### Notes

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