URBAN LANDSCAPES ON PERMAFROST: OGANER CASE STUDY (#0870)

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1. INTRODUCTION

Permafrost plays an important role in the global climate system, the functioning of Arctic environment ecosystems, and affects human activities in the polar regions. Observed climate warming over the last decades have resulted in an increase in permafrost temperature and active-layer thickness in numerous locations across the Arctic. The effects of climate warming on the permafrost system are exacerbated in areas of intensive human activity, particularly in large industrial centers that result in the emergence of urban landscapes on permafrost and which are different from their environmental counterparts. The city of Norilsk, located above 69°N in the Russian Arctic is one of the largest urban landscapes on permafrost.

Norilsk is characterized by severe climate, forest-tundra vegetation and continuous permafrost. It has a high population density, concentrated mining and metal production plants, developed infrastructure of various types and ages. Norilsk is known for exceptionally high pollution levels and represents a nucleus of technogenic impacts on the fragile Arctic environment, including permafrost. Response of the permafrost system to these impacts is exacerbated by the climate warming observed in recent decades, resulting in increase of permafrost temperature and deterioration of the geotechnical environment *(Figure 1).*

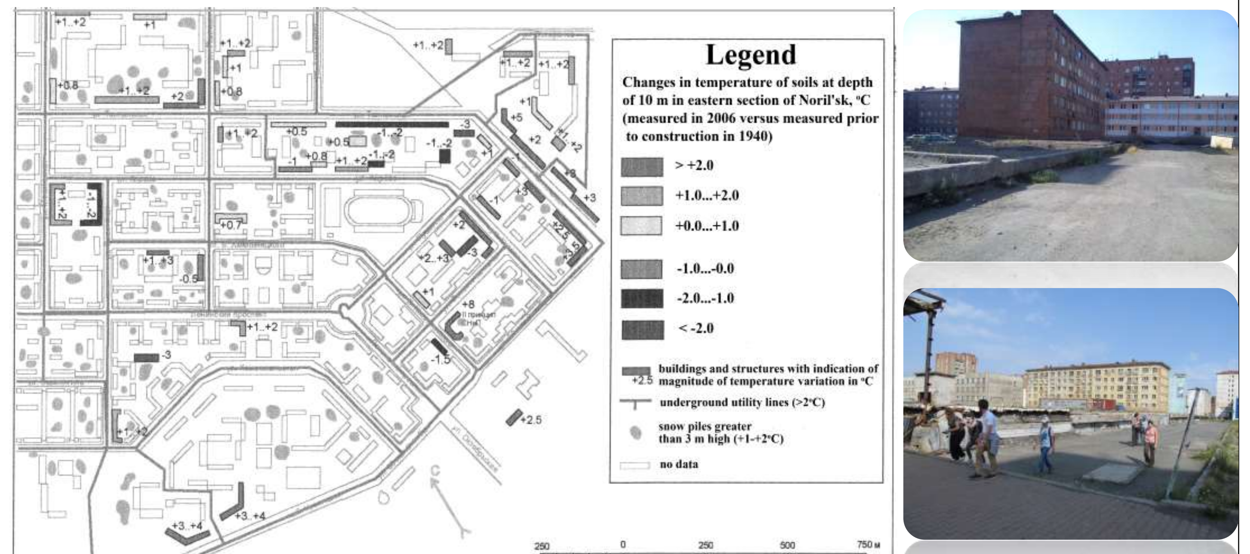

Figure 1. Left: Changes in permafrost temperature prior to construction and in 2006, for the eastern part of Norilsk. Right: Recently demolished buildings in Norilsk (photo by D. Streletskiy, July 2013)

The population of Norilsk was 178,000 in 2013. It requires substantial number of residential housing, however only few houses were built in the last twenty years. Residential houses are typically designed for 50-year lifespan and with the majority of houses built prior to 1980s, Norilsk infrastructure is aging. This situation makes Norilsk administration to look for the ways to sustain population and infrastructure in the city. One of the ways, outlined by strategic city planning committee of 2006 was to build new houses in Oganer, located 8 km east from Norilsk (*Figure 2*).

Difficult engineering conditions, presence of ice-rich permafrost and intensification of thermokarst processes due to vegetation and soil disturbances made construction expensive and problematic. Construction of Oganer faced additional difficulties in 1990s as complicated economic situation, transition to free market economy and uncertain future of the remote cities after collapse of the Soviet Union resulted in substantial population outmigration from many Arctic regions, including Norilsk. Oganer, originally planned as a large satellite city was never completed. Presently, it is represented by only one out of five planned districts, with several 9-story unfinished buildings, a fire station, a school and a hospital *(Figure 2)*.

The combined effects of a warmer climate and human-induced changes in this urban environment led to accelerated deterioration in permafrost geotechnical properties and created potentially dangerous situations with respect to infrastructure and the population in the city. **This paper examines the past, present and future state of permafrost geotechnical properties as an integrative component of urban landscapes in the Norilsk area.**

Figure 2. Left: Oganer city district: unfinished buildings shown in red, orange rectangle is the area of potential future construction. Right: Oganer district. Colored circles showing circle corresponding to the map. Note tundra landscapes with thermokarst in the background (Photo by A. Lapkovsky, July 2006)

2. STUDY AREA

2.1. Urban environment

The first houses in Oganer were built around 1986 on piles using a combination of permafrost and near-surface bedrock *(Figure 3).* Piling foundations were advantageous in permafrost with low ice content and close location of bedrock, however several additional geologic surveys in Oganer revealed that the bedrock extent was much smaller than expected prior to construction. Because road were already built and utilities were in place, the construction continued, but had to deal with ice-rich (40-60%) permafrost. Alternative types of foundations, such as the surface foundations with ventilated bases were implemented. This was a good solution considering the presence of ice-rich permafrost; however problems with ventilation and overestimated structural weight of the structures resulted in deformation of the buildings on surface foundations *(Figure 4*).

Figure 3 . Left: Building constructed using piling foundation on permafrost. The piles can also be seen on the right from the building. Various heights of the piles shows differential frost heave processes over the construction site.
Right: underground utility collector. The heat excess from a network of such collectors is one of the main reasons of permafrost degradation in urban areas, such as shown on Figure 1 for Norilsk (Photo by D. Streletskiy, July 2013.)

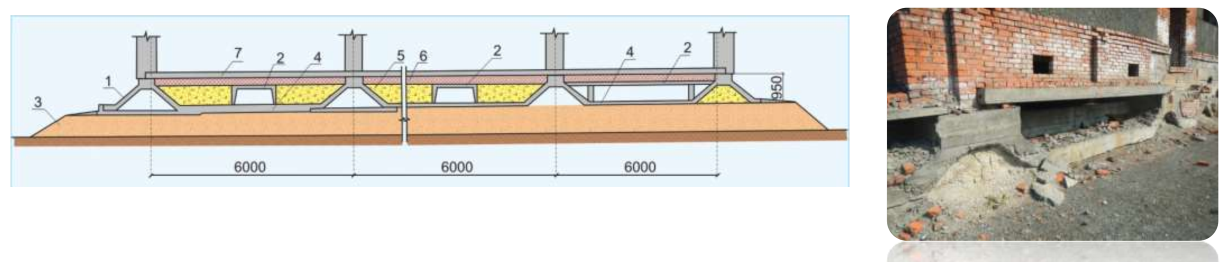

Figure 4. Diagram of surface foundation (author Yury Goncharov) used on permafrost with high ice content (left) and example of deformed building on such foundation in Oganer (right). (Photo by D. Streletskiy, July 2013; diagram from Permafrost Institute, Yakutsk)

2.2. Climate conditions

The climate of Norilsk is characterized by cold winters and relatively warm, but short, summers. The mean annual temperature between 1980 and 2010 was -8.5°C, total precipitation was 465 mm the majority being snow. The mean air temperature during the coldest month (January) was -26.8°C, and during the warmest month (July) was +14.2°C. Between the 1970s and 2000s, mean annual air temperature and precipitation increased by 1.4°C and 10 mm, respectively (*Figure 5*).

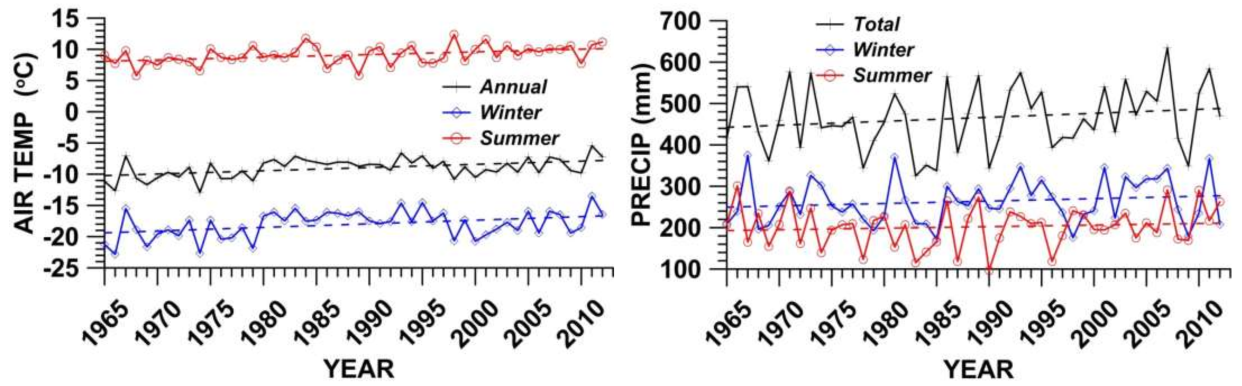

Figure 5. Mean annual, winter and summer temperature and precipitation observed by Norilsk weather station

2.3. Permafrost conditions

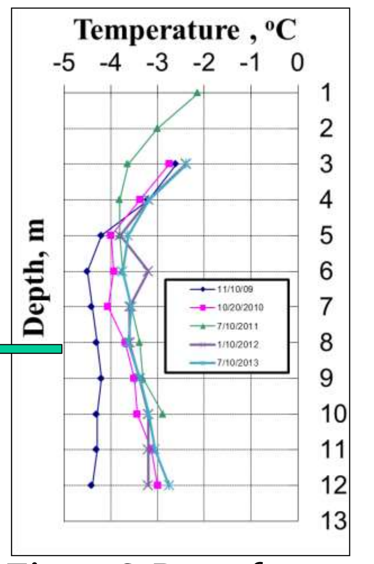

Figure 6. Permafrost temperature in Oganer

The area is characterized by continuous permafrost. Permafrost temperatures in Norilsk city varied from -6…-7 to -0.5°C prior to construction in 1940s and 1960s to -2.5…-0.5°C in 2000s. The combined influence of climatic, environmental factors and rapid technogenic transformations of the ground thermal regime after construction created highly heterogeneous permafrost temperature field (*Figure 1*). Temperatures in Oganer prior to construction were from -5 to -0.5°C, permafrost characterized by high ice content. Permafrost temperature increased over the last 5 years from -5.0 to -3.5°C *(Figure 6*). The active-layer thickness (ALT) data are available only for 2005-2013 from the CALM monitoring site R32 Talnakh located near Norilsk in undisturbed typical polygonal tundra landscape. The mean ALT was 0.92 m (0.81 - 1.03 m).

3. METHODOLOGY

We used a combination of modeling techniques and field observations to evaluate how changes in climatic conditions and human activities affected permafrost geotechnical properties in Norilsk and surrounding areas.

Climatically driven changes in the permafrost-geotechnical environment were evaluated using a model designed to estimate permafrost temperature, active-layer thickness, and foundation bearing capacity, depending on changing climatic conditions, accounting for various landcover and soil characteristics, and geometry of common piling foundations.

Average monthly temperature and winter precipitation from the Norilsk weather station, as well as six experiments from CMIP5 were used as input into the permafrost-geotechnical model. The six models were chosen based on their ability to demonstrate the best performance in matching observed temperature trends in the Russian Arctic. These models were CanESM2 (CanESM), CSIRO-Mk-3.6 (CSIRO) - HadGEM2-ES (HadGEM), GFDL-CM3 (GFDL, IPSL-CM5A-LR (IPSL), NorESM1-M (NorESM).

The projected experiments ran from 2006-2300 under RCP8.5 forcing, the output was rescaled to a 1° x 1° spherical grid for comparative purposes.

To evaluate historic changes in the permafrost-geotechnical environment, we assumed that 30-year reference climatology available prior to construction was used. This procedure would have been required according to the Construction Norms and Regulations used to estimate foundation bearing capacity prior to construction. Several soil types, each characterized by high and low ice content, were used. To assess the effect of snow redistribution on permafrost temperature, two extreme cases were included: one in which no snow accumulates and a second with 0.6 m of snow accumulation by the end of the winter.

To evaluate future changes in permafrost-geotechnical properties, the decade between 1965 and 1975 (further 1970) was selected as a reference period, since a large number of structures were built around this period and because 30-year periods were too computationally demanding to model. Relative changes in climatic, permafrost and geotechnical parameters were calculated for the present (1995-2005 (2000)), near-future (2015-2025 (2020)), mid-century (2045-2055 (2050)) and the end of the century (2085-2095 (2090)).

4. RESULTS AND DISCUSSION

4.1. Climate

According to the six models used in this study, the mean annual air temperature in Norilsk increased by 1.3°C from 1970 to 2000, which agrees with the observational trend from the Norilsk weather station. HadGEM, IPSL and GFDL did the best job in representing the observed trend. According to the best three models, temperature increases of 4, 7 and 11°C is expected by 2020, 2050 and 2090, respectively, under the RCP8.5 forcing (*Figure 7*). There is large uncertainty in snow cover representation across the models, with IPSL predicting a 40 cm increase and HadGEM showing a 30 cm decrease. Overall, snow cover is predicted to increase slightly by the end of the century (*Figure 7*).

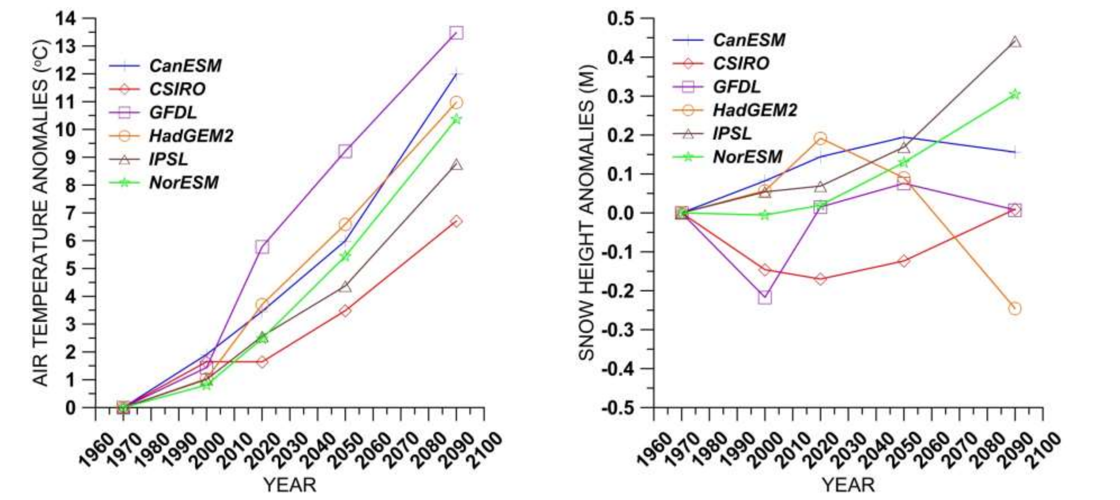

Figure 7. Mean annual air temperature and snow height anomalies relative to decade of 1970s.

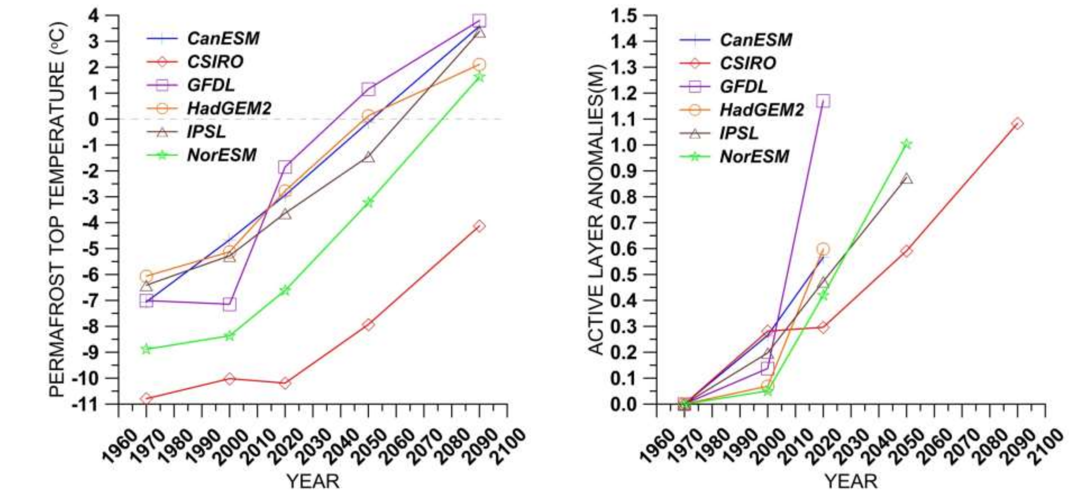

Figure 8. Permafrost temperature and active layer thickness anomalies relative to decade of 1970s using six models.

4.2. Permafrost temperature and active layer thickness

Active-layer thickness was validated using the CALM site located within the climate grid. The average ALT over the observation period was 0.92 ± 0.21 m which is within the range obtained by the model ensemble for the 2000s. The use of all 6 models showed that ALT in 2000 was 13 cm higher than in 1970 and is 0.98 m. ALT is projected to increase. Two out of six models show that by 2050, the active-layer will no longer reach the permafrost layer. Instead, a layer of talik overlying the permafrost will increase. A layer of seasonal freezing will develop at the surface but will progressively decrease by 2090. The remaining four models project an average increase of 1.8 m by 2050 relative to 1970. All models, except CSIRO, show near-surface permafrost disappearance by the end of the century. According to CSIRO, low temperature permafrost will persist throughout the century even under a scenario using the highest possible forcing (Figure 8).

4.3. Foundation bearing capacity

Warmer winter air temperatures and increased snow cover height lead to an increase in permafrost temperature, while warmer summers and, possibly, the role of increasing summer precipitation, resulted in thickening of the active layer. The combination of these factors resulted in an overall decrease of bearing capacity by 2013, relative to previous years (*Figure 9*). For buildings built around the 1960s, the decrease was, on average, 15% (9-30%), while the average for buildings built around the 70s and 80s, it was 21% (11-38%). This indicates that structures built in 1970s and 1980s are more prone to deformations due to climatic loss of bearing capacity than those built in 1960s.

The bearing capacity obtained by the six models show a decrease by 10±9% from 1970 to 2000, which is similar to the estimate of 12% obtained using observational data for the same time period. By 2020, a bearing capacity decrease is projected to be 37±22%, which is higher than safety coefficients for most buildings built in late 1970-80s in the Norilsk area. With a slow pace of new construction and "recycling" of old foundations, it is possible that some of the foundations will still be in place by 2050, in which case the ability of their foundations to support structural weight will decrease by two thirds, according to six models (68±28 %).

Changes in climatic and permafrost characteristics are summarized in the table on the right. **Value is for seasonal freezing layer

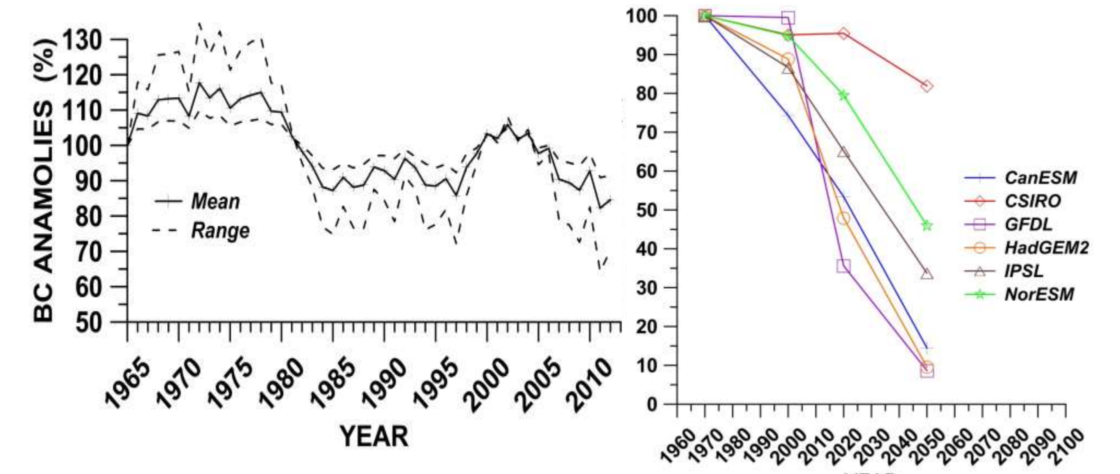

Figure 9. Left: Changes in foundation bearing capacity by 2013 using observational climate. Right: Changes in bearing capacity relative to 1970s using climate input from the six experiments

Table 1. Changes in climatic and permafrost variables from 1970 to 2090

Variable	1970s	2000s	2020s	2050s	2090s
Annual Air Temp (°C)	-12.03 ± 1.7	-10.72 ± 1.7	-8.77 ± 2.6	-6.20 ± 3.0	-1.68 ± 3.5
Relative snow height (cm)	46±10	-3.39 ± 11.9	1.64 ± 9.8	8.27 ± 9.9	10.52 ± 23.5
ALT (m)	0.81 ± 0.4	0.98 ± 0.4	1.40 ± 0.5	0.46 ± 2.1	1.35** ± 1.5
Temperature of the permafrost top (°C)	-7.70 ± 1.8	-6.77 ± 2.1	-4.67 ± 3.2	-1.90 ± 3.3	1.73 ± 3.0
Bearing capacity change (%)	0.00	-10.27 ± 9.2	-36.28 ± 21.0	-67.43 ± 27.7	NA

5. SUMMARY

The economic development of industrial centers on permafrost mandates that housing be adequate to sustain the workforce that dwell in these centers. The foundation bearing capacity used as a quantitative indicator of the ability of foundations to support the structural weight of houses depends on permafrost properties. These properties are, in turn, affected by changes in climatic and environmental conditions and human activities, making bearing capacity an important, comprehensive indicator of changes in urban landscapes on permafrost. The combination of climate warming and human activities in the Norilsk area has resulted in increased permafrost temperature and a decrease in foundation bearing capacity. This trend is projected to continue in the future if adequate measures fail to be taken by the city administration.

ACKNOWLEDGMENTS

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