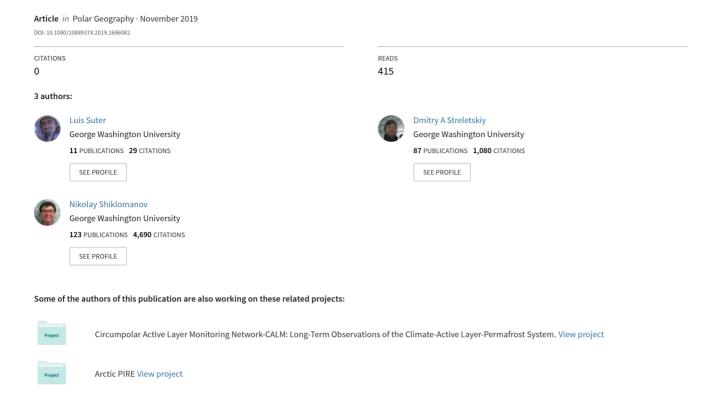
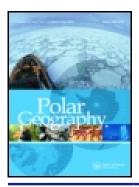
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Assessment of the cost of climate change impacts on critical infrastructure in the circumpolar Arctic

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ABSTRACT

The Arctic is experiencing pronounced climatic and environmental changes. These changes pose a risk to infrastructure, impacting the accessibility and development of remote locations and adding additional pressures on local and regional budgets. This study estimates the costs of fixed infrastructure affected by climate change impacts in the Arctic region, specifically on the impacts of permafrost thaw. Geotechnical models are forced by climate data from six CMIP5 models and used to evaluate changes in permafrost geotechnical characteristics between the decades of 2050-2059 and 2006-2015 under the RCP8.5 scenario. Country-specific infrastructure costs are used to estimate the value of infrastructure affected. The results show a 27% increase in infrastructure lifecycle replacement costs across the circumpolar permafrost regions. In addition, more than 14% of total fixed infrastructure assets are at risk of damages due to changes in specific environmental stressors, such as loss of permafrost bearing capacity and thaw subsidence due to ground ice melt. Regions of Northern Canada and Western Siberia are projected to be particularly affected and may require additional annual spending in the excess of 1% of annual GRP to support existing infrastructure into the future.

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Arctic; infrastructure; climate change; permafrost; economics; GIS

Introduction

The circumpolar Arctic is home to about 4 million people – roughly 0.15% of the world population – but it plays a disproportionally large role in the global economy, contributing 0.6% to global gross domestic product (GDP) (Heleniak & Bogoyavlensky, 2015; Larsen & Huskey, 2015). The Arctic's role in the global economy is only projected to increase, with the region holding rich natural resources, including an estimated 25% of the world's undiscovered oil and gas reserves (Hossain, 2017). Resource and urban development often take place in remote locations and require various types of infrastructure, including buildings, roads, railroads, airports, ports, and pipelines to maintain large-scale economies (Laruelle, 2015; Orttung, 2016). This infrastructure is built at much greater cost relative to temperate regions, due to remoteness and the absence of local production centers (Budzik, 2009; Huskey, Mäenpää, & Pelyasov, 2015).

Meanwhile, the Arctic is warming at twice the rate of the global average (AMAP, 2017). Changing climatic conditions have the potential to improve the accessibility of offshore resources (Stephenson & Pincus, 2018; Stephenson, Smith, & Agnew, 2011) but may also

negatively affect existing infrastructure, which is much larger in scale, and critical to the support of marine activities (Anisimov & Reneva, 2006; Clarke-Sather et al., 2017; Huskey et al., 2015). Land-based infrastructure in the Arctic requires unique solutions in order to withstand severe climatic conditions, including low temperatures, high snow loads, and the presence of permafrost (Frolov, 2015). Permafrost is critical, because the characteristics of the perennially frozen ground are key variables in the design of foundations for various infrastructures.

Permafrost has highly variable temperature, extent, and thickness. This is due to differences in climatic conditions, land cover, and soil properties. The presence of permafrost requires innovative construction techniques designed to decouple frozen ground from the active and latent heat of structures. This is commonly accomplished by elevating buildings and structures using piles anchored in the permafrost (Andersland & Ladanyi, 2003) and/or installing technologies such as thermosyphons to maintain the temperature of soil. The thermal state of permafrost and the thickness of the active layer – a layer just above the permafrost which is subject to annual freezing and thawing – intrinsically affect the ability of foundations to support structures (Shiklomanov, Streletskiy, Grebenets, & Suter, 2017a).

Permafrost warming and active layer thickening (ALT) decreases the bearing capacity of the soil and results in ground subsidence in areas with ice-rich permafrost (Nelson, Anisimov, & Shiklomanov, 2001; Streletskiy, Sherstiukov, Frauenfeld, & Nelson, 2015; Streletskiy et al., 2016; Romanovsky et al., 2017). Where such changes are colocated with infrastructure, their cumulative impacts may result in replacement and costs related to increased maintenance (Grebenets, Streletskiy, & Shiklomanov, 2012; Schweikert, Chinowsky, Espinet, & Tarbert, 2014).

Permafrost temperatures have steadily increased since the 1980s (AMAP, 2017; Streletskiy et al., 2017). Following air temperature trends, increases in permafrost temperature have been greatest in cold permafrost regions of the Alaskan Arctic, Canadian high Arctic, Svalbard, and Northern Siberia (Aalto, Harrison, & Luoto, 2017; Aalto, Karjalainen, Hjort, & Luoto, 2018; Biskaborn et al., 2019; Romanovsky et al., 2017). In lower latitudes, where discontinuous permafrost is more common, permafrost temperature increases are less pronounced, however, ALT is increasing (Shiklomanov et al., 2007; Streletskiy, Shiklomanov, & Nelson, 2012b).

Hazard-risk modeling of climate change impacts has been successfully applied to inform policymakers and the public about potential future environmental conditions (Arndt, 2001; Monmonier, 2008; Tol, 2018). Several studies have demonstrated methodologies to estimate the increase of climate change impacts on infrastructure, within individual Arctic nations including Alaska, Canada, and Russia (Dore & Burton, 2001; Larsen et al., 2008; Melvin et al., 2017; Porfiriev et al., 2017; Streletskiy, Suter, Shiklomanov, Porfiriev, & Eliseev, 2019). Larsen et al. (2008) established relationships between permafrost extent, air temperature increase, and infrastructure's useful lifespan. Melvin et al. (2017) and the Environmental Protection Agency (EPA) (2017) implemented stressor-response models that estimated the impacts of specific hazards using a GIS modeling approach (Chinowsky & Arndt, 2012). Hjort et al. (2018) developed a hazard-risk index to assess the impact of permafrost degradation on infrastructure at the circumpolar scale. Streletskiy et al. (2019) used a geotechnical model to evaluate the cost of climate change impacts in Russian regions with permafrost, based on government statistics on the value of fixed infrastructure by regions downscaled, using gridded dataset of population distribution.

However, an assessment examining the costs needed to maintain and replace Arctic infrastructure is not currently available at the circumpolar scale. Such economically-framed metrics have proven to be effective tools for communicating with business, government, and public (Wihbey & Ward, 2016), all of whom are increasingly active stakeholders in the development of the Arctic.

This study builds on previous works by integrating the infrastructure lifespan replacements model (Larsen et al., 2008), the infrastructure stressor-response model (Melvin et al., 2017), the permafrost geotechnical model (Shiklomanov, Streletskiy, Swales, & Kokorev, 2017b; Streletskiy, Shiklomanov, & Nelson, 2012a), and a compiled geodatabase of Arctic infrastructure, to quantitatively evaluate the cost of climate change impacts on critical infrastructure across the circumpolar Arctic.

Data and methods

Study area

The border to the Arctic is not explicitly defined. This is reflected by varying definitions based on physiographic features, country borders, and various international organizations delineations (CAVM, 2003; Husebekk, Andersson, & Penttilä, 2015; Klüter, 2000; NSIDC, 2018; O'Rourke, 2019; Orttung (Ed.), 2016). The study area of this assessment (Figure 1) conglomerates the maximum land area defined as 'Arctic' by four major organizations: The Arctic Human Development Report, Arctic Monitoring and Assessment Program, Conservation of Arctic Flora and Fauna program, and Arctic Council Emergency Preparedness, Prevention, and Response program. The study area extends further south to include areas with significant permafrost within Alaska, Canada, Norway, Sweden, Finland, and Russia. However, the Scandinavian countries, Finland, Iceland, Greenland, and the Faroe Islands were excluded from the sub-national economic analysis on the basis of minimal fixed infrastructure located on permafrost and a lack of necessary socioeconomic datasets at the appropriate scale and complexity.

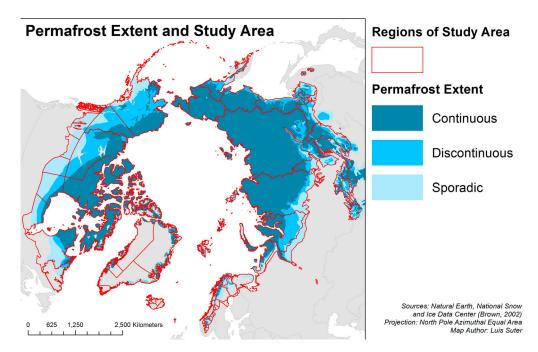


Figure 1. Permafrost extent and administrative regions within the study area.

Arctic infrastructure inventory

At the small geographic scale of this study, infrastructures can be classified as *linear* infrastructure or *point-based* infrastructure. Linear infrastructure includes roads, railroads, and pipelines, while point-based infrastructure applies to buildings, airports, and ports. Publicly available sources of governmental geodata, such as the Alaska Department of Natural Resources, GeoGratis CanVec Series (Canada), the Norwegian Mapping Authority, the Swedish Land Survey, the Finnish National Landsurvey, and OpenData Russia were used to compile a circumpolar infrastructure database (Table 1). Governmental sources were supplemented by publicly available repositories of geospatial data, namely DIVA GIS, Natural Earth, and GeoFabrik (OpenStreetMap data). These open-source datasets were cleaned and classified to extract relevant infrastructure types, with priority given to the governmental datasets in cases of overlap.

Governmental GIS data on buildings was particularly variable in terms of attributes and granularity. For Alaska, a dataset that was previously used by Melvin et al. (2017) in a regional analysis of permafrost thaw impacts was employed. This dataset includes attributes of public building size and value, among others, however, it does not include private

Table 1. Infrastructure inventory with sources by country.

	Infrastructure	
Country	type	Source
Alaska	Roads	Alaska Department of Natural Resources
	Railroads	Alaska Department of Natural Resources
	Pipelines	Alaska Department of Natural Resources
	Airports/Ports	Arctic Marine and Aviation Transportation Infrastructure Initiative (AMATII)
	Buildings	Personal Correspondence with Dr. April Melvin (NAS, PRB)
Canada	Roads	GeoGratis CanVec Series – Transportation Features
	Railroads	GeoGratis CanVec Series – Transportation Features
	Pipelines	GeoGratis CanVec Series – Transportation Features
	Airports/Ports	Arctic Marine and Aviation Transportation Infrastructure Initiative (AMATII)
	Buildings	GeoGratis CanVec Series – Manmade Features
celand	Roads	National Land Survey of Iceland
	Railroads	National Land Survey of Iceland
	Pipelines	N/A
	Airports/Ports	Arctic Marine and Aviation Transportation Infrastructure Initiative (AMATII)
	Buildings	National Land Survey of Iceland – Structures
Vorway	Roads	Norwegian Mapping Authority – Road Network
,	Railroads	DIVA GIS
	Pipelines	Norwegian Petroleum Directorate
	Airports/Ports	Arctic Marine and Aviation Transportation Infrastructure Initiative (AMATII)
	Buildings	Norwegian Mapping Authority (Kartverket) – Official Addresses
Sweden	Roads	Swedish Land Survey GeoData Portal
	Railroads	Swedish Land Survey GeoData Portal
	Pipelines	N/A
	Airports/Ports	Arctic Marine and Aviation Transportation Infrastructure Initiative (AMATII)
	Buildings	Swedish Land Survey GeoData Portal
inland	Roads	Finnish National Land Survey
mana	Railroads	Finnish National Land Survey
	Pipelines	Finnish National Land Survey
	Airports/Ports	Arctic Marine and Aviation Transportation Infrastructure Initiative (AMATII)
	Buildings	Finnish National Land Survey
Russia	Roads	Open Data Russia (Supplemented with DIVA GIS and OpenStreetMap)
iassiu	Railroads	Open Data Russia (Supplemented with DIVA GIS and OpenStreetMap)
	Pipelines	Proposed and Existing Russia Oil, Gas, and Product Pipelines (ArcGIS Online)
	Airports/Ports	Arctic Marine and Aviation Transportation Infrastructure Initiative (AMATII)
	Buildings	State Fund for Assistance to Reform housing and communal services (database accessed
	buildings	through GitHub)

residences. In Russia, detailed data on homes was accessible through the website of the State Corporation Fund for Assistance with Housing and Communal Services, including information on the number of dwellings per building (ReformaGKH, 2018). In Canada, Iceland, Norway, Sweden, and Finland, point-based building and address datasets were gathered from governmental statistical sources. While this aggregated inventory is not fully integrated m in terms of common attributes or granularity, it represents some of the best collated, publicly available, data at the circumpolar scale.

In the absence of high-quality and uniform geospatial data at the circumpolar scale, and considering the small geographic scale of analysis, assumptions were made that the ratio of infrastructure built on permafrost is proportional to the extent of permafrost within each corresponding permafrost zone (Streletskiy et al., 2019). Permafrost extent is classified as island (<10% coverage), sporadic (10%–50% coverage), discontinuous (50%–90% coverage), and continuous (90%-100% coverage). Therefore, infrastructure assets within each grid cell were weighted by the 0.1, 0.5, and 0.9 coefficients for sporadic, discontinuous, and continuous permafrost zones, respectively, and no infrastructure was assumed to be present on island permafrost.

Selection of climate input

This study utilized climate inputs from six preselected general circulation models (GCMs) included in the CMIP5 project (WCRP, 2011). GCMs are computationally-driven simulations of the global climate system that account for multiple climate components (i.e. oceans, cryosphere, land cover, etc.), as well as the complex interactions and exchanges of mass and energy between them (Gramelsberger & Feichter, 2011). The model ensemble for this study was selected based on a documented ability to successfully reproduce historical temperature trends in the Russian Arctic, (Anisimov, Kokorev, & Zhil'tsova, 2013) and was previously applied for climate change impacts assessments of the Arctic regions (Melvin et al., 2017; Shiklomanov et al., 2017b; Streletskiy et al., 2019). These CMIP5 models are: CanESM2 (CanESM), CSIRO-Mk-3.6 (CSIRO), HadGEM2-ES (HadGEM), GFDL-CM3 (GFDL) IPSL-CM5A-LR (IPSL), and NorESM1-M (NorESM).

The RCP 8.5 scenario was used in order to provide the upper limit of impacts for which to plan (Riahi et al., 2011). Based on continiual political trends, socioeconomic development, and observed climate change, this scenario looks likely to occur (Lewis, King, & Perkins-Kirkpatrick, 2017). The decade of 2006-2015 was used as a baseline of present climatic conditions, while the decade of 2050-2059 represents the future climate scenario. These periods were chosen based on the typical lifespan of most infrastructure types and the planned trajectory of long-term development projects. For each reference period, daily means of temperature and precipitation were used as modeling input. Precipitation co-occuring with negative daily temperatures is assumed to accumulate as snow. The mean of the six models was used to represent the best estimate of the projected climate change within each climatic grid-cell, while standard deviation was used as a measure of variability around the mean. The spatial resolutions of the models varied, so all climate inputs were interpolated from the original grids of varying resolution to a unified 0.5×0.5 -degree latitude/longitude grid, using an inverse distance method with a linear decay function.

Changes to permafrost temperature and active layer thickness were assessed for two scenarios relevant to infrastructure stability. The first case assumed that snow and vegetative cover are removed, as would be the case for buildings, roads, and railroads. The second case assumed that snow and little vegetative cover are present, representing close to natural conditions, which is further used to evaluate stability of above-ground pipelines.

Permafrost geotechnical modeling

The permafrost model employed in this study was developed by Streletskiy et al. (2012a) and is used to estimate active layer thickness and permafrost temperature based on climatic and environmental variables, which are then used to estimate the permafrost bearing capacity. The permafrost component of the model is based on the modified solution to the general Stefan problem of heat conduction with a moving phase boundary and accounts for the effects of snow cover, vegetation, and soil properties (such as texture, moisture, organic content, and ice content). The geotechnical part of the model is based on a set of formulations developed to estimate the bearing capacity of frozen soils for different common foundation types as a function of permafrost temperature and maximum annual thaw propagation. The bearing capacity calculations are based on an experimentally-derived set of equations available from Russian construction norms and regulations for common types of soils, and accounts for salinity, peat presence, and ground ice content.

To allow the intercomparing between regions with permafrost regardless of local construction designs, this study assumed all buildings are built on piling foundations and all pipelines are built above ground within areas of permafrost. Two common types of 'standard pile' designs are assumed for buildings and pipelines, following approaches in studies by Streletskiy et al. (2012a), Fedorovich and Targulyan (1991), and the U.S. Department of Defence (2004).

Permafrost degradation is commonly associated with ground subsidence. Nelson et al. (2001) developed a settlement index model based on the relative change of the maximum seasonal thaw depth – or ALT – and the volumetric proportion of ground ice in the soil. This study applies the approach developed by Nelson et al. (2001), using changes in ALT calculated within the permafrost-geotechnical model and volumetric ice content data obtained from the International permafrost map (Brown, Ferrians, Heginbottom, & Melnikov, 2002). The permafrost map classifies ground ice as low, medium, or high. These zones are assigned quantitative ground ice volume values of 10%, 20%, and 40%, based on the ranges established by Brown et al. In this study, ground subsidence was calculated as the change in ALT, multiplied by the ice content within each grid cell-calculated from the IPA permafrost map, interpolated to a 0.5×0.5 grid to match the climate input. Considering that the actual distribution of ground ice is highly heterogeneous, and may represent a major + source of uncertainty in the results of this study, average ice content is the best estimate of ground ice content within each grid cell.

Modeling infrastructure costs

The value of roads, railroads, pipelines, (per km), ports, and airports (per unit) was obtained from Larsen et al. (2008) and adjusted for inflation to 2017 US dollars (\$). The value of infrastructure was assumed to remain constant throughout the timespan of the study. Country-level variations in infrastructure value were accounted for using country-specific comparative price levels (OECD, 2018) as multiplication factors.

Data on the value of buildings is not available in a common format across the Arctic. For example, in Alaska, the dataset included an attribute of value, but only included public buildings.

In Russia, highly accurate spatial information on the location of housing units and the number of dwellings within unit is available, but does not inlude any accessible value data. In this case, regional statistics on average household size, square meter living space per person, and the cost per square meter were used to estimate this value (Russian Federal State Statistics Service, 2018). In the remaining countries, a similar methodology was applied, however, buildings or registered addresses were assumed to be single-family residences. These assumptions were necessary due to the spatial scale of the study and lack of uniform geospatial data on buildings.

The changing infrastructure lifecycle replacement costs from the present period to the future period were estimated following the approach of Larsen et al. (2008). The baseline annual cost of replacing infrastructure was calculated by dividing each infrastructure type's cost per unit by each infrastructure type's designed useful lifespan.

The adjusted annual cost was calculated using the same formula, but with each infrastructure's useful life adjusted for climate change. The ratio used to calculate infrastructures adjusted useful life was based on relationships between permafrost extent and projected air temperature increases, established by Larsen et al. (2008). As the useful lifespan of infrastructure shortens, it requires replacement more often, representing increases in costs related to addressing regular wear and tear.

Within stressor-response models, each infrastructure type is associated with specific environmental hazards that impact it - in this case those hazards relevant to the Arctic context - and the cost of addressing their impacts. Damages, set equal to the replacement cost of infrastructure, were quantified using engineering & material science validated relationships between each infrastructure type, and the stressors associated with projected climate change, after given thresholds are crossed. The thresholds in this study were based off previously established research when available (Larsen et al., 2008; Melvin et al., 2017), and supplemented by consultation with engineering and infrastructure experts. The thresholds were set to account for common safety factors in engineering design. If a threshold was crossed, it was assumed that infrastructure would have to be repaired or replaced to maintain functionality. In more detailed regional studies, these thresholds should be further adapted to meet regional or local construction codes.

Costs were first analyzed on the national level, and further analyzed on the regional level in particularly affected countries. On the regional level, costs were framed against measures of economic prosperity, including gross regional product (GRP) and governmental spending. In the absence of projected economic data for the study regions, GRP data for 2016 was assumed to remain constant. GRP for the US (Alaska), Canada, and Russian regions was obtained from the national statistical databases. Government spending data for Alaska was referenced from the National Association of State Budget Officers State Expenditures Reports for 2016 (NASBO, 2016).

Results

Value of infrastructure

The total value of six types of infrastructure assets within the study area is about \$146 billion. Russia, Norway, Canada, and US (Alaska) account for over 90% of infrastructure assets. Norway has the highest asset value though their quantity of buildings on permafrost is relatively minor. The high values of the Scandinavian countries are partially due to the extremely high OECD cost-levels. Among the six infrastructure categories, buildings and structures account for 67% of the total value of infrastructure assets, while roads account for an additional 17%. Railroads and pipelines account for about 5% each, while airports and ports combine for another 5%.

The distribution of infrastructure types varies. In Norway, buildings account for 90% of national infrastructure asset value. However, building foundations in Norway are typically anchored in bedrock and thus are less impacted by permafrost degradation. However, it is not possible to filter these out of the GIS datasets, given the scale and quality of the data. Norway is thus excluded from the regional analysis, based on expert opinion. On the other hand, in Russia buildings account for 70% of infrastructure value, and it is typical for buildings in Russia's urban Arctic environments to have foundations anchored in non-bedrock permafrost (Shiklomanov et al., 2017a). Buildings account for a further 58% of infrastructure value in Alaska and 41% in Canada.

Roads account for about 10–17% of assets within Russia, the US (Alaska), and Sweden, yet represent a more signficant proportion of infrastructure in Canada (37%), Finland (68%), and Iceland (81%). Canada contains almost 42% of the total road assets in the study area, while Russia accounts for 64% of pipeline assets in the study area. Russia also contains by far the largest rail network in the Arctic.

The importance of airports and ports is clear in the context of Alaska and Canada. By value, Alaska contains about 44% of circumpolar airport assets and Canada about 36%. Within the US (Alaska), airports represent about 16% of total infrastructure assets; in all the other countries, the share of the value of airports to total assets is under 10%. For ports, Canada and Norway have the largest share, holding 23% and 32% of circumpolar assets respectively.

Projected climate change in the Arctic

There is significant variability between the model projections of climate change at the circumpolar scale. The mean temperature increase derived from the combination of six models employed is 3.6° C. The GFDL model shows the most pronounced warming of up to 5°C across the study area, while the CSIRO model is the most conservative with 2.2 °C projected across the study area. Overall, the six models employed are in greater agreement regarding subarctic regions with maritime climates and areas with sporadic to discontinuous permafrost. The model ensemble has a higher variability in areas with continental climate, characterized by continuous permafrost and mountainous regions.

The largest temperature increases (Figure 2) are projected to occur over the interior of the Siberian continental landmass, Northern Canada, and North/Central Alaska. Among these regions, all models but CSIRO agree that Siberia will be most impacted, while CSIRO projects the most warming in Alaska and Northern Canada.

The change in average annual precipitation (Figure 2) increase across the ensemble is 72 mm, but the range is considerable: some areas show slight drying (up to -34 mm) while other areas show significant wetting, up to +226 mm. The GFDL model predicted the highest precipitation increases with a mean of 72 mm across the study area, with regions of the Pacific sector, such as Chukotka, Alaska, and Yukon showing increases greater than 200 mm. CSIRO is the most conservative model, projecting a 37 mm increase (-149 mm / 271 mm) across the study area.

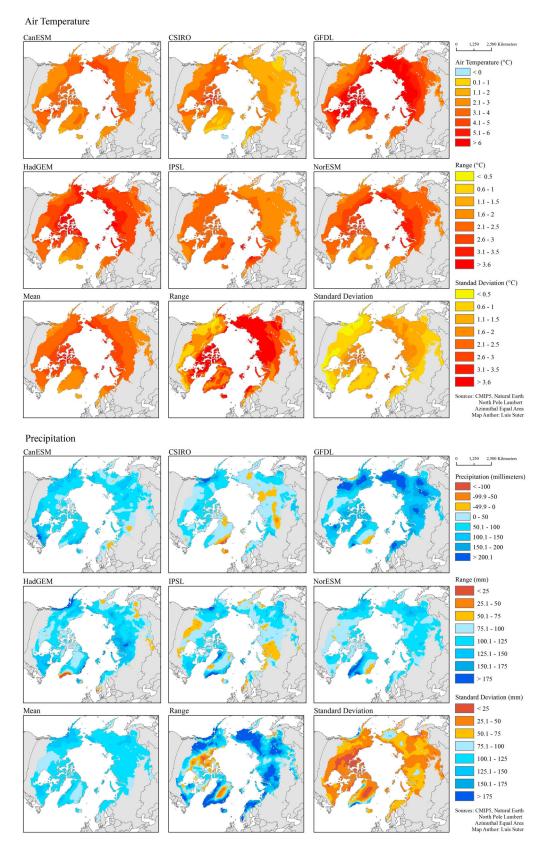


Figure 2. Model outputs showing changes in Mean Annual Air Temperature and Precipitation between 2005-2010 and 2050-2059, under RCP8.5.



Changes in permafrost characteristics

Permafrost temperature and active layer thickness

In all models, there is strong agreement that permafrost will warm significantly across much of the Arctic. In natural conditions - where snow and vegetation remain undisturbed ground temperature warming is expected to be less intense, increasing 3.7°C (1.3°/5°C) about 0.1°C lower than the scenario with snow removal.

Under conditions where snow and vegetation are absent, such as under buildings, the ensemble mean projects an increase of 3.8°C, ranging from 1.6° to 6.5°C. All models show by consensus that the most significant warming will take place in the High Arctic, which is characterized by continuous permafrost. In the Subarctic, where discontinuous permafrost is more common, the warming trend is less pronounced.

A negligible area of permafrost coverage in Iceland is projected to cool slightly by CSIRO, which is the least pessimistic model. The CSIRO model (2.34°C; -1.1°/6.4°C) projects warming to remain below 2°C across most of Siberia. Even this conservative model, however, projects increases of up to 4°C in Alaska and Canada.

Given natural conditions, the ensemble mean predicts that ALT will decrease by 0.31 m (-0.56 m/0.80 m), generally 0.1 m less than the scenario with snow and vegetation removal (0.41 m; -0.78 m/0.76 m). Negative values indicate the loss of near surface permafrost during the time period of the study, and a shrinking of the seasonal freezing layer (Melvin et al., 2017). The variability amongst the models is comparable across the Arctic, with only small portions of central Alaska and Chukotka seeing a standard deviation greater than 0.4 m.

Without snow, the active layer is expected to thicken significantly throughout the Arctic. The ensemble mean predicts an increase in ALT of 0.41 m across the Arctic, with a range of -.78 m to 0.76 m. The models generally agree on the spatial distribution of changes in ALT. All the models agree that the greatest increases will occur in continental Siberia, northeast Alaska, and Yukon. In southwest Alaska, near surface permafrost is expected to disappear entirely in some models.

Loss of bearing capacity and ground subsidence

The ensemble mean reduction of bearing capacity under the natural scenario is 41%, with a maximum of 69% reduction. The models generally agree on the spatial distribution of changes, with the edges of permafrost zones more significantly impacted, and pockets of relative stability within central Siberia. Consensus is strongest within the continental interiors, while higher standard deviations are notable near the edges of the study area.

The bearing capacity of soil around buildings - where vegetation is removed through paving and snow is regularly cleared - is projected to decrease more than in the natural scenario. The ensemble mean indicates a 43% loss of soil bearing capacity across the study area. The maximum losses are projected around the southern limits of the permafrost zone. The consensus between models in this case is relatively strong. Standard deviation is under 15% for much of the study area, especially in the central areas of Siberia, Canada, and Alaska.

Yukon, Yamal-Nenets, and the southern Russian permafrost regions are particularly impacted by bearing capacity losses (Figure 3), while in central Siberia, permafrost is predicted to remain slightly more stable. The highest projected decreases are in Eastern Siberia, Northwest Alaska, Northeast Canada, and Chukotka. Around the edges of the study area, in southwest Alaska and southern Russia, there is less model agreement due to

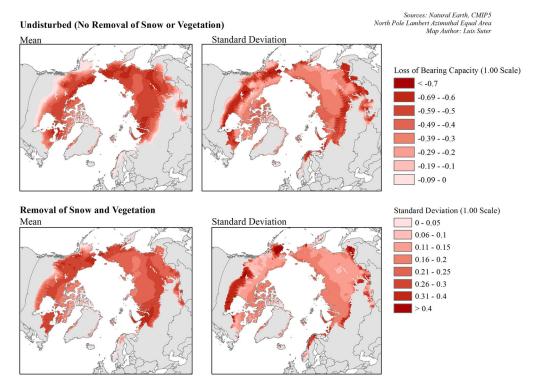


Figure 3. Model outputs for change in bearing capacity between 2005–2010 and 2050–2059, under RCP8.5.

the variability in predictions of near-surface permafrost disappearance. In these areas, standard deviations above 40% are noted.

Given the natural scenario, significant portions of territory currently occupied by near-surface permafrost – especially those in Alaska – are expected to become permafrost free. The model ensemble mean ground subsidence is projected to be 0.1 m, with some regions above 0.3 m. These changes are most intense in the areas of the highest predicted subsidence, where large increases in ALT overlap with areas of high ground ice content. There is greater agreement towards the edges of the study area, indicated by a standard deviation lower than 0.1 m. Only in parts of central Alaska and Russia does this standard deviation exceed 0.1 m (Figure 4).

Lifecycle replacement costs

The lifecycle replacement costs to maintain Arctic infrastructure (Table 2) are projected to increase by 27.7%, or about \$15.47 billion, by 2050–2059. Pipelines are projected to be the most impacted infrastructure relative to baseline lifecycle costs, with an increase of over 60% by 2059. Significant cost increases, of over 40%, are projected for roads, railways, airports, and ports. Building lifecycle costs are only projected to increase by about 12%, due to the long intended lifespan of this infrastructure. Roads account for the largest share of all increased lifecycle costs, at 39% of the total, while costs related to building maintenance account for a further 22% of total costs. The increased lifecycle replacement costs for pipelines, railroads, and airports are \$1.83 billion, \$1.60 billion, and \$2.05 billion, respectively, accounting for 35% of

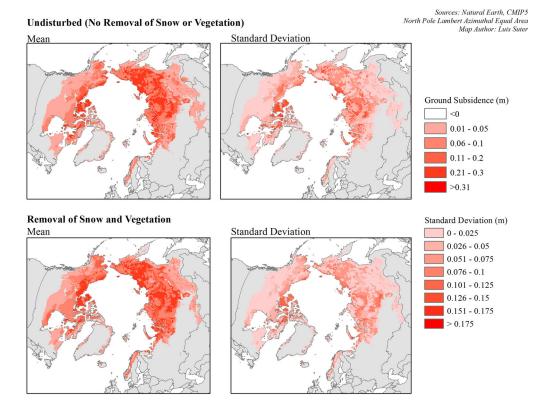


Figure 4. Model outputs for ground subsidence between 2005–2010 and 2050–2059, under RCP8.5.

the total increase. Costs associated with ports are projected to account for the remaining 4% of lifecycle cost increases. However, damage to ports is underestimated in this study, as the model could not account for the environmental stressor of coastal erosion.

Table 2. Baseline and climate forced lifecycle replacement costs by 2059, for infrastructure types & countries.

& countries.	Deceline.	Casta with Climata		Davaget In success from Climate			
Catagory	Baseline Lifecycle Replacement Costs	Costs with Climate Forcing	Difference	Percent Increase from Climate			
Category	, .	3		Change			
Infrastructure	(\$ Millions)	(\$ Millions)	(\$ Millions)	%			
Roads (Paved)	\$15,055.97	\$21,142.97	\$6087.00	40.4%			
Rail	\$3978.49	\$5576.98	\$1598.50	40.2%			
Pipelines	\$3001.90	\$4827.56	\$1825.65	60.8%			
Buildings	\$27610.02	\$30948.61	\$3338.58	12.1%			
Airports	\$4951.72	\$6999.09	\$2047.37	41.3%			
Ports	\$1340.23	\$1913.52	\$573.29	42.8%			
Total	\$55,938.34	\$71,408.73	\$15,470.39	27.7%			
Country	(\$ Millions)	(\$ Millions)	(\$ Millions)	%			
Canada	\$12,865.02	\$17,190.46	\$4325.44	33.6%			
Russia	\$24,085.29	\$30,716.65	\$6631.36	27.5%			
United States	\$7061.91	\$9620.59	\$2558.68	36.2%			
Norway	\$10,718.64	\$12,313.67	\$1595.03	14.9%			
Sweden	\$780.19	\$988.47	\$208.28	26.7%			
Finland	\$381.50	\$517.22	\$135.72	35.6%			
Iceland	\$45.79	\$61.67	\$15.87	34.7%			
Total	\$55,938.34	\$71,408.73	\$15,470.39	27.7%			

Category Infrastructure	Total Asset Value (\$ Millions)	Percent of Total Assets Impacted by 2059 %			
Roads (Paved)	\$25,027.67	18.92%			
Rail	\$7663.67	12.30%			
Pipelines	\$7553.11	15.02%			
Buildings	\$98,179.46	13.29%			
Airports	\$5878.75	25.89%			
Ports	\$1630.50	13.65%			
Total	\$145,933.17	14.80%			
Country	(\$ Millions)	%			
Canada	\$27,977.44	18.75%			
Russia	\$40,339.14	31.87%			
United States	\$16,044.38	21.79%			
Norway	\$51,760.96	0.01%			
Sweden	\$3796.27	0.00%			
Finland	\$2657.83	0.00%			
Iceland	\$3357.15	0.00%			
Total	\$145,933.17	14.80%			

Russia incurred the greatest projected increases in lifecycle costs – about 43% of the total. To mitigate the impacts of increased wear and tear, Russia may have to spend \$6.63 billion for lifecycle replacement by 2059, a 27.5% increase relative to their baseline. Canada is projected to incur \$4.33 billion during the same time period, which represents a 33.6% increase from baseline lifecycle replacement costs and 28.0% of total increased costs. Alaska and Norway incur \$2.56 billion and \$1.60 billion in increased maintenance costs, respectively. Finland and Iceland are projected to incur much lower total costs, but these still represent 35% increases, relative to the baseline.

Impacted infrastructure value

The value of damaged infrastructure (Table 3) across the entire Arctic is \$21.6 billion dollars by the begining of 2059. This damage represents about 15% of the total value of infrastructure assets included in this study. The impacts are projected to be highest in Russia, where about 32% of infrastructure is estimated to be impacted. Comparatively, about one fifth of total assets are estimated to be affected by in the US (Alaska) (22%) and Canada (19%). Within the other Arctic countries, no substantial damages related to permafrost thaw and precipitation increases were found.

Within each infrastructure category, about 15%–20% of assets are projected to be impacted, except for airports, where about 26% of assets are projected to experience damages due to climate change. In Russia buildings are at the greatest risk, while in North America mainly roads and airports are impacted. This reflects historic development trends, with Russia's concentrated population in urban areas, while Canada and Alaska are characterized by smaller, more dispersed settlements.

Regional costs

On a regional level, the lifecycle replacement and stressor-response models indicated that Sakha Republic, Alaska, Yukon, Northwest Territories, Krasnoyarsk Krai, and Yamal-Nenets AO are the most impacted. By 2059, Sakha Republic and Alaska are each expected

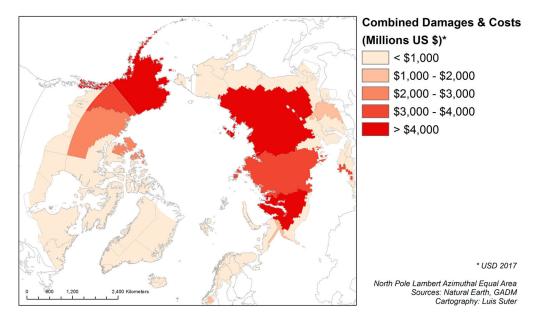


Figure 5. Total lifecycle costs & damages to infrastructure by 2060, by region.

to incur over \$6 billion in combined repair and replacement costs, while Yamal-Nenets is expected to incur about \$4 billion. Yukon and Krasnoyarsk Kari are projected to incur \$3.9 billion and \$3.2 billion, respectively (Figure 5).

Costs relative to gross regional products

The ability of regional budgets to absorb these increased costs is tied to their economic prosperity, which is often measured in gross regional product (GRP). The mean annual costs to address increased lifecycle replacement costs and direct damages due to climate change exceed 3.7% of annual GRP in Yukon. This figure lies at 1.5% and 1% of GRP for the Northwest Territories and Nunavut. Within Russia, Magadan, Sakha Republic, and Zabaykalsky Krai are particularly impacted, with mean annual combined costs accounting for between 1% and 1.4% of 2016 GRP. Yamal-Nenets, Komi Republic, and Krasnoyarsk are also impacted, with about 0.3% of GRP needed to address mean annual cost increases (Table 4).

Table 4	 Annual 	Total	Costs	till	2059	as a	Percent	of	Annual	GRP	(2016).
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Regions (< 0.01% of GRP)	Country	Annual Total Costs till 2059 as Percent of Annual GRP (2016)
Yukon	Canada	3.73%
Northwest Territories	Canada	1.46%
Zabaykalsky	Russia	1.41%
Nunavut	Canada	1.06%
Sakha (Yakutia)	Russia	1.05%
Magadan	Russia	0.98%
Gorno-Altay	Russia	0.38%
Nenets	Russia	0.37%
Alaska	USA	0.31%
Yamal-Nenets	Russia	0.31%
Republic of Buryatia	Russia	0.29%
Komi Republic	Russia	0.28%
Krasnoyarsk	Russia	0.28%
Chukotka	Russia	0.25%



Discussion

These ratios may seem low, but the sums become consequential when considered in relation to government spending, or the contribution of individual industries to GRP. For example, the cumulative mining sector in Yukon contributed about 11% to GRP in 2015 (Yukon Department of Economic Development, 2016). Addressing the impacts of climate change may cost the region the equivalent of a third of total mining output. In a region of high costs and small profit margins, these increased costs are significant.

In Russia, government spending accounted for 18% of 2016 GDP (Global Economy, 2018). The 1% of GRP incurred to address climate impacts thus represents almost 6% of the government budget, which implies that the projected share of annual GRP going towards mitigating climate damages in Sakha, Zabaykalsky, and Magadan represents a significant portion of the government budget.

In Alaska, the mean annual costs of addressing some of these climate impacts registered as about 0.3% of 2016 GRP, which was about \$50 billion. In relation, government spending by the state of Alaska in 2016 amounted to about \$10 billion (NASBO, 2016), representing 20% of GRP. This indicates that mean annual costs could account for close to 1.5% of annual state government spending. This is more than Alaskan state government spending on all public assistance (food programs, assistance for needy families) for fiscal year 2016, which accounted for 1.4% of state budget expenditures (NASBO, 2016). This comparison of fiscal impacts to regional budgets may present a clearer picture of the effects of climate damages in a region, as GRP includes resource wealth that is moved out of the region.

Comparison to previous studies

As a comparison to this study, Larsen et al. (2008) predicted a 10% to 20% increase in infrastructure lifecycle costs for Alaska by 2030, and 10% to 12% by 2080. This study estimates a 36% increase for the same region by 2059, almost triple the increase predicted by Larsen et al. On a circumpolar level, the lifecycle replacement model predicted a 27% increase in upkeep costs. The infrastructure stressor-response model used in this study predicted \$3.5 billion of climate damages in Alaska, which corresponds well with the Melvin et al. (2017) estimates for the region, which projected \$5.7 billion (USD 2017) of direct damages in Alaska by 2100. The variability in results compared to the aforementioned studies is likely a result of the differing time periods, GCM ensembles employed, and differences in the infrastructure inventories used.

Within Russia, Streletskiy et al. (2019) estimated that costs related to permafrost thaw impacts would amount to over \$100 billion, vastly surpassing the \$19.5 billion estimated in this study. The infrastructure inventory vastly underestimated the value of infrastructure in the Russian Arctic. The Streletskiy et al. (2019) study utilized Russian Federal Statistical Services data, which provided a monetary breakdown of total infrastructure assets by region. This governmental data indicated \$249 billion of fixed infrastructure in Russian permafrost regions, while the six types of infrastructure conglomerated for this study only estimated \$40 billion. This indicates that there remain significant gaps in the availability of Arctic infrastructure data, especially in areas where governmental geospatial data is difficult or impossible to obtain.

Further studies estimated higher indirect costs of climate change, specifically within Russia. Porfiriev et al. (2017) based their estimates on two previous studies on the indirect economic impacts of climate change (Hope & Schaefer, 2016; Schuur et al., 2015). These indirect costs, such as the release of methane into the atmosphere from thawing permafrost, contributed significantly to the projected costs, adding \$160 trillion by 2100, or about \$1.9 trillion annually across the Arctic region. This could cost some Russian Arctic regions upwards of 5 to 6% of annual GRP to address (Porfiriev et al., 2017).

Hjort et al. (2018) employed a hazard-risk model to produce a high-resolution circumpolar geohazard map, assesing how changes in circumpolar permafrost conditions could impact infrastructure. The areas of highest risk identified in that study correlate well to the regions of highest-cost identified in this study, as Alaska, Yukon, YNAO, and Sakha (Yakutia) were among the most directly impacted. However, this study shows that some of the highest risk regions also contain the strongest economies (as measured by GRP), which may help them offset some mitigation costs.

Further considerations

There are factors not resolved by this study, which are difficult to model at its scale; these includes national construction codes, maintenance standards, and their associated costs. Moreover, the model employed in this study focuses mainly on permafrost and does not integrate several important environmental variables, such as coastal erosion (Fritz, Vonk, & Lantuit, 2017; Melvin et al., 2017), frost-heaving (Abdalla, Fan, McKinnon, & Gaffard, 2015; Melvin et al., 2017), and hydrology (Instanes et al., 2016). Furthermore, the study is unable to resolve the role of non-climatic factors, which have significant influence on infrastructure stability and sustainability; these factors include maintenance capacity, social capital, and political authority, all of which are important for infrastructure stability and the ability to mitigate future climate impacts (Grebenets et al., 2012; Shiklomanov et al., 2017a).

The results also reveal differences between the climate inputs used between the models, which reflects the uncertainty inherent in most climate models (Räisänen, 2007).

There is significant spatial variability between the model results at the circumpolar scale. Northeastern Siberia, the Canadian Arctic Archipelago, and Iceland are areas with relatively high uncertainty in air temperature projections, while in Western Russian Arctic and Alaska, the models show greater agreement. There is even more considerable uncertainty in the projections for precipitation. The improved climate models from upcoming releases, such as CMIP6, could be used to improve this analysis (Eyring et al., 2016). The uncertainty in climate projections and the coarse parametrization of soil characteristics, including ground ice content, are major sources of uncertainty in the permafrost model outputs used to calculate bearing capacity and ground subsidence.

With these considerable limitations in mind, the results of this study should be interpreted with caution. However, the results provide a valuable estimate of the distribution of permafrost thaw related impacts on infrastructure at the circumpolar scale, as well as an analysis of the costs related to those impacts at the national and regional scales. The results show that there are several regions of the Arctic, including Yukon, Alaska, YNAO, and the Sakha Republic (Yakutia) where more granular assessments should be conducted.

By modeling climate change impacts using economics, this study aims to scaffold more effective policy and business advice metrics. These metrics are intended to guide sustainable policy in a way that speaks to stakeholders who are not typically engaged with climate science. Some academics, policymakers, and private industries have expressed optimism about future resource production considering climate change, especially within Russia

(Anisimov & Reneva, 2006). As the Arctic is already a high-priced region, any additional costs could impact budgets and fiscal priorities (Streletskiy et al., 2019). Estimates of the costs of climate change should be considered by planners and developers interested in expanding into the Arctic's emerging market, to anticipate potential economic outcomes and to ensure that private industries and governments alike are prepared to address the costs of climate change.

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