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ESTIMATING FUTURE COSTS FOR INFRASTRUCTURE IN THE PROPOSED CANADIAN NORTHERN CORRIDOR AT RISK FROM CLIMATE CHANGE

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FOREWORD

THE CANADIAN NORTHERN CORRIDOR RESEARCH PROGRAM PAPER SERIES

This paper is part of a special series in *The School of Public Policy Publications,* investigating a concept that would connect the nation's southern infrastructure to a new series of corridors across middle and northern Canada. This paper is an output of the Canadian Northern Corridor Research Program.

The Canadian Northern Corridor Research Program at The School of Public Policy, University of Calgary, is the leading platform for information and analysis on the feasibility, desirability, and acceptability of a connected series of infrastructure corridors throughout Canada. Endorsed by the Senate of Canada, this work responds to the Council of the Federation's July 2019 call for informed discussion of pan-Canadian economic corridors as a key input to strengthening growth across Canada and "a strong, sustainable and environmentally responsible economy." This Research Program will benefit all Canadians, providing recommendations to advance the infrastructure planning and development process in Canada.

This paper, "Estimating Future Costs for Infrastructure in the Proposed Canadian Northern Corridor at Risk from Climate Change", falls under theme *Environmental Impact* of the program's eight research themes:

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Program Director, Canadian Northern Corridor Research Program

ESTIMATING FUTURE COSTS FOR INFRASTRUCTURE IN THE PROPOSED CANADIAN NORTHERN CORRIDOR AT RISK FROM CLIMATE CHANGE

Nathan S. Debortoli, Tristan D. Pearce and James D. Ford

ABSTRACT

This paper reviews current climate change projections for northern Canada and considers what these mean for infrastructure development in the proposed Canadian Northern Corridor (CNC). We focus on chokepoints along the corridor's notional route and estimate future costs of infrastructure along the chokepoints. We draw upon climate change projections at the end of the century (2100) using information from several climate variables sourced on the CMIP6 and CMIP5 reports. Climate variables include means and extreme values for temperature, precipitation, wind and their indirect impacts on physical features: permafrost, freezing rain and wildfires. In terms of infrastructure costs, we investigate investment costs and the useful life of nine sectors within transportation, energy and buildings infrastructures. The findings of our analysis show that mean temperatures within the CNC area could increase by 10.9ºC, and precipitation by 45 per cent by 2100. Climate change could create chokepoints along the CNC route, affecting key areas essential for transportation flow. Central regions of the corridor are projected to have a higher probability of receiving concomitant impacts on several chokepoints, including combined threats from the increasing frequency of wildfires, freezing rain and permafrost thaw. Adding a climatic layer to investment costs within CNC chokepoints can increase infrastructure costs by more than 101 per cent. Transportation engineering infrastructure, electric power infrastructure and the institutional buildings sectors are most likely to be impacted. Just considering a climate layer to current infrastructure increases costs by more than $12 billion for several hazards such as freezing precipitation (especially Alberta and BC), $7 billion for wildfires (especially BC) and more than $400 million for permafrost (especially Alberta and BC). Infrastructure built along the CNC route will need to be designed to remain functional under different climatic conditions that predominate today. Chokepoints will dictate how buildings and transportation infrastructure should be planned.

KEY MESSAGES

- The Canadian Northern Corridor (CNC) region is expected to experience warming temperatures and increasing precipitation. At some locations, mean temperatures could increase by 10.9ºC, and mean precipitation by 45 per cent by 2100 in some areas.
- Climate change could create chokepoints along the CNC route, affecting key areas essential for transportation flow. Central regions of the corridor are projected to be more likely to receive concomitant impacts on several chokepoints, including combined threats from increasing frequency of wildfires, freezing rain and permafrost thaw.
- Adding climate change impacts to investment costs such as the CNC chokepoints can increase infrastructure costs by more than 101 per cent. Transportation engineering infrastructure, electric power infrastructure and the institutional buildings sectors are mostly likely to be impacted.
- Baseline variables (not including climate projections) show that current costs soar when these are internalized in cost analysis up to $12 billion for freezing precipitation (especially Alberta and BC), $7 billion for wildfires (especially BC) and more than $400 million for permafrost (especially Alberta and BC).
- Infrastructure built along the CNC route will need to be designed to remain functional under different climatic conditions that predominate today. Chokepoints will dictate how buildings and transportation infrastructure should be planned.

EXECUTIVE SUMMARY

Northern Canada is one of the world's regions most affected by climate change (CC). Climate change-related warming in the North has the strength to change air masses locally, regionally and continentally, affecting several climatic variables (i.e., liquid and solid precipitation patterns and extremes, humidity, maximum and minimum temperature means and extremes, surface winds, jet stream's location and strength and so on) producing negative cascading effects to ecosystems and the human communities that depend on them. More extreme events in temperature and precipitation hasten physical processes such as the thaw of permafrost, increase the severity and intensity of drought, which may fuel more intense wildfires, and can shift extreme episodes of freezing rain to more northern latitudes, and increase the strength of storms. Such events can increase the risk of infrastructure decay by boosting the degradation of materials at a much faster rate, and push infrastructure past critical thresholds. This decrease in the life cycles of infrastructures will consequently increase investment and repair costs now and in the future.

This paper reviews current climate change projections for northern Canada and considers what these mean for infrastructure development in the proposed Canadian Northern Corridor (CNC). It focuses on particular chokepoints along the corridor's national route and estimates future costs of infrastructure along the chokepoints. We draw upon CC projections at the end of the century (2081–2100) using information from several climate variables sourced on the CMIP6 and CMIP5 reports. Climate variables include median, 10th and 90th percentiles and extreme values for temperature, precipitation and wind. Baseline information for climate-related physical features including permafrost and wildfires was also collected. In terms of infrastructure costs, we investigate investment costs and the useful life of nine sectors within transportation, energy and built infrastructures. To calculate our costs, we used several references from the literature adapting previous CC cost calculation methods on infrastructures in North American and Arctic regions using a combination of climate variables and infrastructure investment costs indicators in Canada. Our analysis is mostly focused on a high-level cost where we include the infrastructure investment costs data for Alberta, British Columbia, Manitoba and the Northwest Territories. A high score in the accumulation of climatic stressors, referred to as “chokepoints” within the CNC route, influenced our choice of these four regions.

Our results considered a discount rate of three per cent and include the following key findings. Adding a climatic layer to investments costs such as the CNC chokepoints can increase infrastructure costs by more than 101 per cent. Transportation engineering infrastructure, electric power infrastructures and the institutional buildings sectors are the ones to be most impacted. Baseline variables using current information (not including climate projections) showed that internalizing the climate lenses to cost analysis increased costs to $12 billion for freezing precipitation (especially Alberta and BC), $7 billion for wildfires (especially BC) and more than $400 million for permafrost (especially Alberta and BC). CC costs are higher for hazards related to extreme rainfall, surface winds and changes in mean temperatures. Extreme rainfall within a period of five days caused higher costs for BC and Manitoba, indicating a possibility of increased damage related to floods. Rainfall within a one-day period had higher costs for Alberta and BC, indicating that infrastructure could be more prone to flash floods or landslides in these locations.

Projected increases in CC costs were higher when considering extreme rainfall in five days in Manitoba by +200 per cent. Other significant increases include extreme rainfall in one day in Alberta by +90 per cent. Thawing degree days (TDD) influencing permafrost changes is the most important variable for all regions with costs increasing by more than 1,000 per cent with most cost impacts on institutional buildings and oil and gas engineering construction.

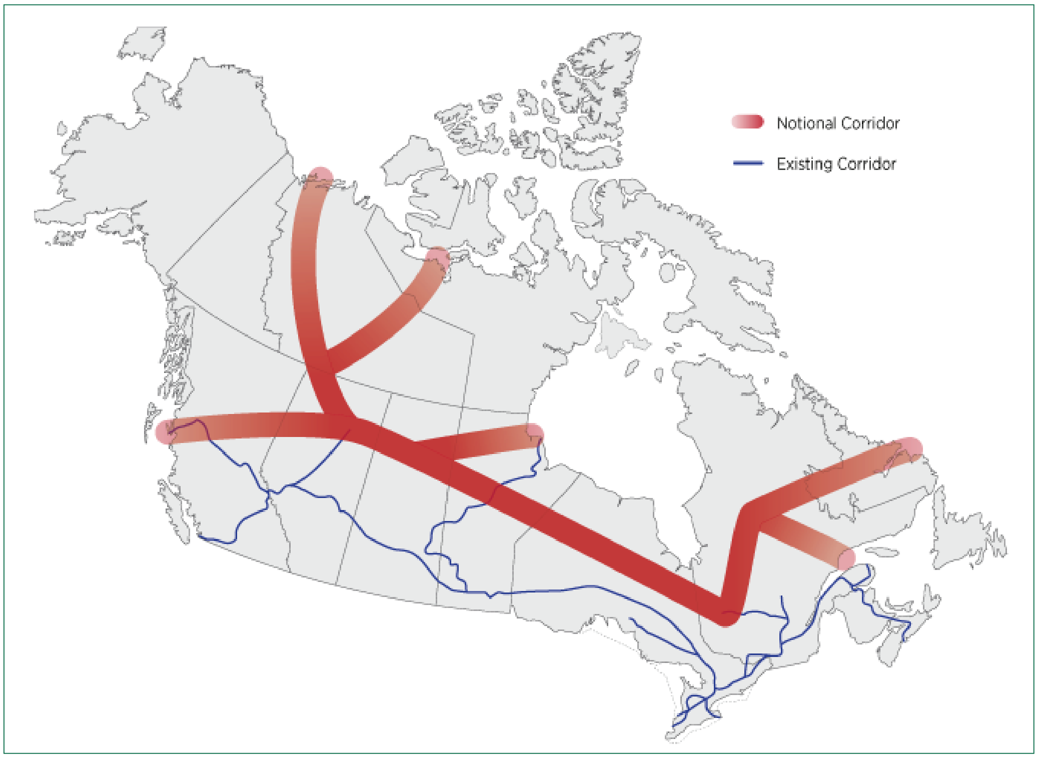
In terms of study limitations, the lack of data for certain areas of the CNC limited cost function development that aimed to foresee costs at a finer scale. Furthermore, we were unable to add costs related to delays in transportation, freight and other indirect delay costs associated with possible infrastructure chokepoints due to a high uncertainty in the available cost values and issues with the reliability of data in uninhibited/remote regions of northern Canada.

1. INTRODUCTION

Northern Canada is one of the world’s regions most affected by climate change (CC) (IPCC 2021). Climate change-related warming in the North has the strength to change air masses locally, regionally and continentally, affecting several climatic variables (i.e., liquid and solid precipitation patterns and extremes, humidity, maximum and minimum temperature means and extremes, surface winds, jet stream’s location and strength and so on), producing negative cascading effects to ecosystems and the human communities that depend on them. More extreme events in temperature and precipitation hasten physical processes such as the thaw of permafrost, increase the severity and intensity of drought, which may fuel more intense wildfires, and can shift extreme episodes of freezing rain to more northern latitudes and increase storm strength. Such events can increase the risk of infrastructures' degradation by increasing the decay of materials at a much faster rate, and push infrastructure past critical thresholds. This decrease in the life cycles of infrastructures will consequently increase investment and repair costs now and in the future (Larsen et al. 2008).

The proposed Canadian Northern Corridor (CNC) is a multi-modal right-of-way (ROW) stretching across northern Canada (Sulzenko and Fellows 2016). The ROW would be one to 10 km in width and approximately 7,000 km in length. It would facilitate the development of multiple modes of transportation and infrastructure such as road, rail, pipelines, telecommunications, electricity transmission and others (e.g., increased shipping) that would increase Canada's export capacity (Sulzenko and Fellows 2016).

Figure 1. Route of the Canadian Northern Corridor as proposed by the University of Calgary School of Public Policy (Sulzenko and Fellows 2016).



Projected future climate change could pose serious challenges to the CNC concept (Pearce et al. 2021). Building, operating and maintaining infrastructure in northern Canada is already inherently challenging due to remoteness and climate. Climate change is being experienced in this context, exacerbating existing risks and creating new challenges and opportunities for built infrastructure (Ford, Bell and Couture 2016; Palko and Lemmen 2017). Thus, past climate can no longer be considered a reliable guide in planning infrastructure (Suter, Streletskiy and Shiklomanov 2019). The construction, operation and maintenance of infrastructure within a CNC would have to be undertaken with a clear understanding of expected future climate impacts and associated costs.

This paper is a part of a larger program that explores multiple issues related to the potential development of the CNC such as climate impacts, corridor governance, defining meaningful consultation and potential funding approaches for the corridor's establishment, governance and regulatory oversight. This paper specifically reviews current climate change projections for northern Canada and considers what these mean for infrastructure development in the proposed CNC. It focuses on particular chokepoints along the corridor's notional route and estimates future costs of infrastructure along the chokepoints. First, we draw upon CC projections at the end of the century (2100) using information from several climate variables sourced on the CMIP6 and CMIP5 reports for the proposed CNC route. Climate variables include means and extreme values for temperature, precipitation, wind and their indirect impacts on physical features: permafrost, freezing rain and wildfires. Next, we investigate investment costs and the useful life of nine sectors within transportation, energy and buildings infrastructures that could be built within the proposed CNC. To calculate our costs, we used several references from the literature, adapting previous CC cost calculation methods on infrastructures in North American and Arctic regions using a combination of climate variables and infrastructure investment costs indicators in Canada. We focused our analysis mostly on a high-level cost perspective where we include the infrastructure investment costs data for Alberta, British Columbia, Manitoba and the Northwest Territories. A high score in the accumulation of climatic stressors, referred to as "chokepoints" within the CNC route, influenced our choice of these four regions.

2. CLIMATE CHANGE PROJECTIONS FOR NORTHERN CANADA

The latest IPCC AR6 report affirms that human influence increased the global surface temperature by +0.8°C and +1.3°C between 2010 and 2019 compared to 1850–1900, with greenhouse gases (GHGs) being the main engine of tropospheric heating since 1979. In northern Canada between 1948 and 2016, temperatures increased by +2.3°C, with most prominent changes during the wintertime, +4.3°C, and +1.6°C in the summertime (Zhang et al. 2019). Changes in temperature have specifically affected minimum temperatures with decreasing frost days, consecutive frost days and ice days (Vincent et al. 2015; 2018). Snowfall precipitation from 1948 to 2012 has relatively increased in northern Canada with an addition of +7.3 days per year, and heavy snowfall +2.3 days per year (Mekis et al. 2015; Vincent et al. 2018). The loss of the Arctic ice sheet has increased four-fold since the 1990s and the retreat of world glaciers is unprecedented in the last 2,000 years. Sea ice in the Arctic summer has seen the smallest extent of the last 1,000 years. In northern Canada, sea ice extent and multi-year ice have decreased since 2008 (Derksen et al. 2018; Cohen et al. 2019). Arctic sea ice has decreased by 10 per cent in March and 40 per cent in September between 2010 and 2019 compared to the 1979–1988 period (IPCC AR6 2021). Multi-year ice has been replaced more rapidly by seasonal first-year ice (Comiso 2012; Babb et al. 2019). Recent physical changes in the characteristics of ice have led to unstable sea ice especially during summertime, creating hazards for shipping activities and community travel (Ford et al. 2019; Barber et al. 2018; Howell and Brady 2019). Changes in ice thickness are fostering new opportunities for travel routes in the high Arctic with increased traffic of visitors into communities (Dawson et al. 2020).

In northern Canada, snow-cover extent has been reduced during spring months (April through June) and fall months (October through December) (Brown et al. 2017; Mudryk et al. 2018). Snowfall observations by northern communities indicate that the snow quality is wetter and snow cover has substantially decreased (Ford et al. 2016). Permafrost impacts include increased thawing of ground ice and thickening of the active layer[1] during summer months. Historical analysis in northern Canada has shown rates of temperature increase related to permafrost varying among regions from +0.1 to +0.9°C (Ednie and Smith 2015; Smith et al. 2017; Romanovsky et al. 2017; Allard, Sarrazin and Hérault 2015). Changes in permafrost are hard to predict since they can be influenced by several variables such as rainfall, snow accumulation and changes in vegetation (Kokelj et al. 2015); however, thermokarst[2] (landforms related to permafrost) changes have become more recurrent in northern Canada (Beck et al. 2015; Olefeldt et al. 2016; Jolivel and Allard 2017; Mamet et al. 2017). As unstable permafrost areas become widespread, bearing capacity will decay, risking more than 19 per cent of Canada's infrastructure. Damages will increase life-cycle replacement costs and are projected to exceed C$4 billion annually (Suter et al. 2019).

Glaciers and ice caps in northern Canada have decreased sharply in the last 15 years. Losses range from 22 gigatonnes to 67 gigatonnes between 1995 and 2010 with further acceleration after 2015. Loss of glaciers in a medium-emissions scenario is projected to continue between 18–96 per cent of total volume towards the end of the century (Clarke et al. 2015; Radić et al. 2014). Such losses are worrying for streamflow and water resources in the North (Derksen et al. 2018; Abdalati et al. 2004; Jacob et al. 2012; Harig and Simons 2016; Clarke et al. 2015; Fyfe et al. 2017). Lakes in northern Canada have experienced rapid drainage as surrounding permafrost thaws (Hinzman et al. 2005; Smith et al. 2005; Fortier, Allard and Shur 2007). In northern watersheds, where flow regimes are nival or mixed nival-pluvial, there are projected shifts to more pluvial flow regimes, with higher annual flows due to increasing precipitation trends at high latitudes (Poitras et al. 2011; Thorne 2011; Vetter et al. 2017). Water levels are expected to be affected variably. For example, the thawing of permafrost is expected to accelerate, which could result in rapid shrinking or drainage of lakes and water levels in some locations across northern Canada (Bonsal et al. 2019). For example, Canada's northernmost lake, Ward Hunt Lake, which had previously remained perennially frozen, melted completely in 2011 and 2012 (Paquette et al. 2015). Increasing temperatures, combined with changes to ice strength and streamflow peak periods are also projected to influence earlier river ice breakup in the spring in northern regions (Cooley and Pavelsky 2016). These could also increase the probability of floods in communities.

Coastal areas will be subject to numerous climate-related impacts, each of which will interact with the others. This includes sea level, permafrost thaw, the loss of sea ice, larger waves, increasing water temperatures, an increase in the frequency of extreme water levels and an increase in erosion as coasts are exposed to harsher weather-related conditions. For example, relative sea level[3] has risen along the Beaufort Sea coastline more quickly than the global mean due to land subsidence, while the eastern Arctic and Hudson Bay

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1 The soil layer above permafrost that freezes and melts each year (Derksen et al. 2018).

2 Thermokarst is a process in which the thaw of ice-rich permafrost and ground ice creates characteristic landforms (IPCC 2013).

3 Relative sea level is current sea level, or changes or projections to sea level, at a specific location, and is primarily influenced by global sea level change and vertical land motion at that location (IPCC 2013).

have experienced a decline in relative sea level[4] (Cohen et al. 2019). The decline in sea ice extent can potentially increase wave energy and wave height with greater fetch[5] conditions (Thomson and Rogers 2014). Shoreline orientation, wind direction and shoreline bathymetry will dictate the size and impacts of greater wave activity (Serafin et al. 2019; Thomson et al. 2016; Greenan et al. 2018). In the Canadian Arctic there has been an observed positive correlation between open water, air temperature and storm intensity and occurrence (Perrie et al. 2012; Vermaire et al. 2013). Models project that areas of greater relative sea level rise will experience a greater frequency and magnitude of storm surges that produce extreme water levels (Greenan et al. 2018). Rising sea level, increasing ocean water temperatures and decreasing sea ice extent and thawing of permafrost have increased erosion and thermal erosion in some areas, particularly in northern Canada (Obu et al. 2017; Derksen et al. 2018; Irrgang et al. 2018). The Gulf of St. Lawrence and areas of the northern coast are particularly sensitive to erosion because they are low-lying, consist of softer materials and have high ground ice or permafrost content. The loss of sea ice and increased wave weight and energy have exposed these areas to erosion and thermal erosion from stronger wave action and warmer ocean water (Ford et al. 2016; Savard, van Proosdij and O'Carroll 2016; Derksen et al. 2018). Coastal areas in the Beaufort Sea region (high ground ice content) have meant coastline loss between 0.5 and 1.5 metres a year (Konopczak, Manson and Couture 2014) and erosion has reached as high as 22.5 metres a year (Solomon 2005).

Across northern Canada, shifts in the distribution of species have been documented and attributed to climate change (Nantel et al. 2014). There has been a loss of habitat or disruption of balances and food webs due to climate-related conditions such as sea ice loss, forest fires, thawing permafrost and increased hypoxia[6] extent (Hutchings et al. 2012; Steiner et al. 2015; Greenan et al. 2018). These changes and disruptions could decrease species and ecosystem productivity, lead to species extinction and create potential for the introduction of new diseases and invasive species, but could also result in increasing productivity and richness in some instances (Nantel et al. 2014). For example, there could be increased northern movement of several commercial fish species and associated fishing activity, although significant uncertainties remain in how climate change will affect fish, especially for small-scale fisheries common in northern Canada (Galappaththi et al. 2019; Falardeau and Bennett 2020). Declining access and availability of wildlife species have been observed to be compromising food security, especially for Indigenous populations whose food systems are closely linked to traditional foods (Wesche et al. 2010; Hlimi et al. 2012; Skinner et al. 2013; Kenny et al. 2018; Lam et al. 2019).

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[4] The uplift (rise) or subsidence (drop) of the ground surface at a location due to processes such as glacial isobaseline adjustment (e.g., the surface underneath large glaciers or ice sheets will subside under the mass of the ice and rise after the glacial mass has decreased or disappeared) (James et al. 2014).

[5] The open water distance between two bodies (e.g., land and sea ice). Larger fetch correlates to larger waves and increased wave energy (Lemmen, Warren and Mercer Clarke 2016).

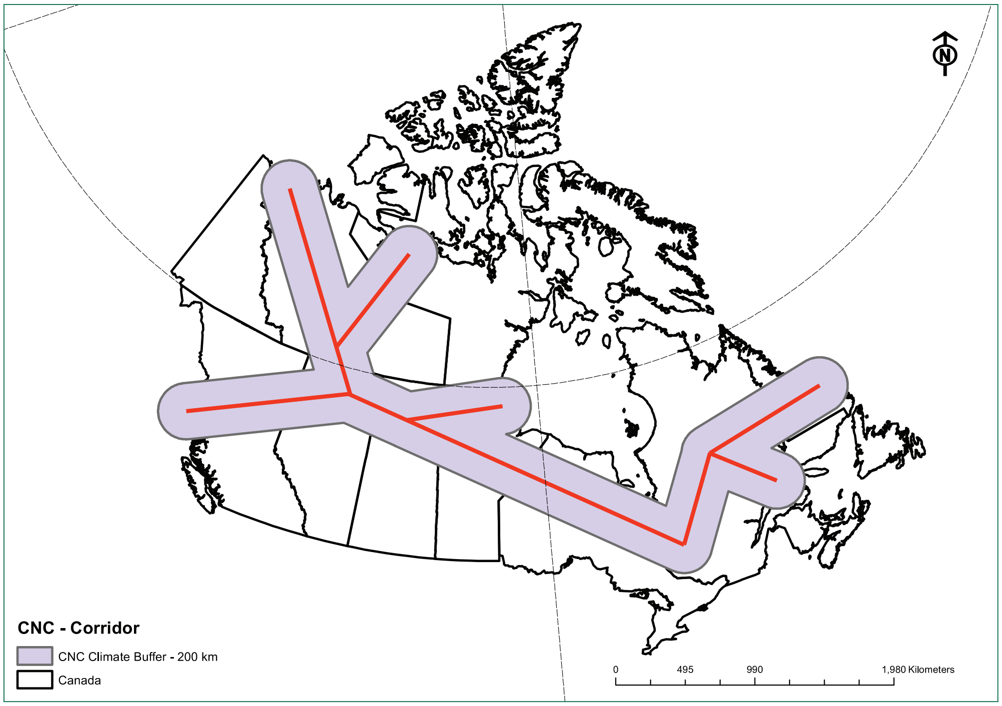
[6] A deficiency in oxygen available in a water body (e.g., the ocean) (IPCC 2013).

2.1 CLIMATE CHANGE PROJECTIONS AND THE CANADIAN NORTHERN CORRIDOR

This section reviews different climate projections from the IPCC AR6 and AR5 reports for North America including the Arctic region and synthesizes the information for the CNC. The climate variables and scenarios analyzed were calculated to consider a 200-km buffer region for the CNC. We consider the mean (mean), 10th and 90th percentiles for all variables for AR6 and AR5 scenarios as follows. The scenarios include a baseline (1850–1900) and future projections including the SSP5-8.5 scenario (2081–2100) for the latest AR6 report and future projections from AR5 RCP8.5 and RCP 4.5 scenario (2081–2100). We focused on the high-emission scenario to provide the upper limit of impacts for which to plan (Riahi et al. 2011; Suter et al. 2019). Based on continual political trends, socioeconomic development and observed CC, the 8.5 scenario from CMIP5 and CMPI6 looks likely to occur (Lewis, King and Perkins-Kirkpatrick 2017). Climate projections from the AR6 include the CMIP ensemble, which includes 33 models depending on the variable analyzed. The climate projections from AR5 CMIP include 24 models also depending on the variable analyzed supplementary materials 1–2. The newest CMIP6 results have generally higher values for our variables if compared with the previous CMIP5 projections. This indicates that the models are predicting larger and more intense changes than what was previously expected in AR5.

To understand how these projections affect the CNC more specifically, we created a buffer zone of 200 km enveloping the corridor. With this buffer zone, we were able to calculate and provide low and upper limits for climate and physical variables (CVs) specific to the corridor (Figure 2).

Figure 2. Map of the proposed Canadian Northern Corridor (CNC). Red lines indicate the 10-km wide corridor area.



Because CMIP5 and CMIP6 projections in the IPCC atlas did not include indices on extreme snowfall in one day (SnowMax1-day), thawing degree days (TDD) and snow cover duration (SNC) variables, we had to perform a special treatment sourcing these variables on the Arctic CORDEX modelling groups simulations, including the medians of the two ensembles (ARCTIC north to 63N and NA south to 63N) that are interpolated with nearest neighbour on the GMFD grid (0.25 lat-lon). Therefore, we warn that results for these variables may not catch the same potential variability from CMIP5/6, reducing the consistency of results for these variables.

Below, we compare the annual patterns for physical and environmental variables considering the CMIP5 and CMIP6 ensembles.[7] Values for these are available in Table 1.

Table 1. Annual warming relative to CMIP6 SSP2-4.5 and SSP5-8.5 (rel. to baseline 1850–1900) & CMIP5 RCP4.5 and RCP 8.5 2081–2100 scenarios within the CNC buffer areas.

Variables	CMIP5 Ensemble		CMIP6 Ensemble	
	RCP8.5 2081-2100	RCP4.5 2081-2100	SSP5-8.5 2081-2100	SSP2-4.5 2081-2100
PR	Up to +37% increase	Up to +20% increase	Up to +45.2% increase	Up to +28.3% increase
Rx1-day	Up to +39%	Up to +21.3%	Up to +46%	Up to +31.4%
Rx5-day	Up to +34.4%	Up to +18.4%	Up to +40.8%	Up to +27.5%
SF	NA	NA	Up to -1.3%	Up to -5%
SFC	From -4.6% to +8.8%	NA	NA	NA
SIC	Up to -40.1%	NA	Up to -57%	Up to -29%
SIT	Up to -100% decrease	NA	NA	NA
SND	From -96.9% to -11.2%	NA	NA	NA
SPEI-12	From -0.8 to +0.4	NA	NA	NA
SPI-6	NA	NA	Up to +172.5%	Up to +151.9%
T	Up to +9.2°C	Up to +6.1°C	Up to +10.9°C	Up to +8.3°C
TN	Up to +9.8°C	Up to +6.4°C	Up to +12.2°C	Up to +8.9°C
TX	Up to +8.6°C	Up to +5.7°C	Up to +10.5°C	Up to +7.8°C

Source: Adapted from CMIP6 and CMIP5.

Temperatures Mean, Max and Min (T, TX and TN): Both CMIP5-6 ensembles indicate a high increase in mean (T), max (TX) and min (TN) temperatures throughout the CNC. The increase is most important for the northwestern and central areas, especially considering TN. TX will increase most in the western part of Hudson Bay. The region of least concern is the western part of the corridor. Temperature increases are higher by almost 1°C in the CMIP6 projections.

[7] IPCC AR6: T = Change deg °C; TX = Change deg °C; TN = Change deg °C; PR = Change (%); Rx1-day = Change (%); Rx5-das = Change (%); SF = Change mm/day; SPI-6 = Change (%); SIC = Change (%). IPCC AR5: T = Change deg °C; TX = Change deg °C; TN = Change deg °C; PR = Change (%); SPI-12 = increase or decrease; SFC = Change (%); SIT = Change (%); SND = Change (%); SIC = Change (%).

Rainfall Precipitation (PR): There is no decrease in precipitation (rainfall) in the CNC. Highest increases in precipitation are concentrated in the northwestern and eastern regions. Precipitation increase is less important towards the south. Extreme precipitation falling in one to five days will also increase by almost half, the most impacted areas concern the northwest, east and western part of the CNC. The highest increase favours total precipitation values falling in one day. CMIP6 projections indicate a greater increase in precipitation compared to CMIP5.

Snowfall Precipitation (SF) and Snowfall Depth (SND): Snowfall precipitation sees practically no changes with a slight decrease in the western part of the CNC. On the other hand, snowfall depth will decrease substantially in the western, eastern and southern CNC.

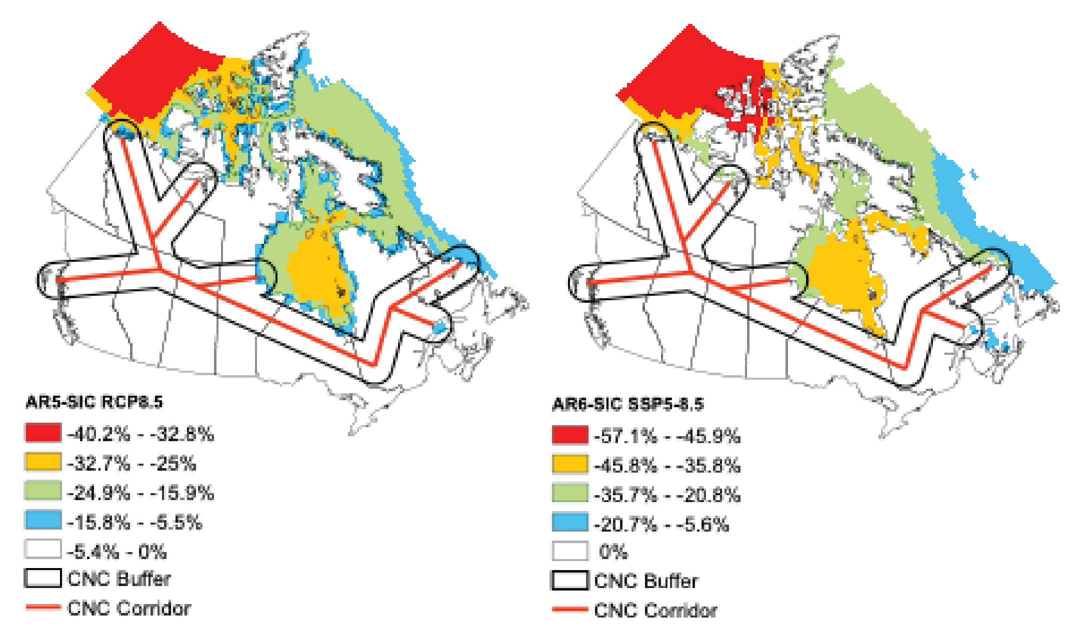
Standardized Precipitation Index (SPI-6 months) and Standardized Precipitation Evapotranspiration Index (SPEI-12 months): Drought impacts for a six-month period are higher for the northwest and eastern regions of the CNC. For a 12-month period, index results indicate an increase in drought especially in the northwest, west and central areas of the CNC. The area of least concern is the eastern region. It is important to notice these time-scale differences in drought patterns. Short-term (six-month) drought seems to affect more the eastern region of the CNC compared to the 12-month pattern.

Surface Winds (SFC): Surface winds will decrease in the eastern and western parts of the CNC and increase in the northwestern Beaufort Sea and the western areas of Hudson Bay.

Sea Ice Thickness (SIT): Sea ice thickness is projected to decrease substantially throughout the entire region. Most impacted areas include the Labrador Sea, Hudson Bay and Beaufort Sea. Impacts range from -43 per cent to -100 per cent.

Sea Ice Concentration (SIC): Sea ice concentration is projected to decline sharply towards the end of the century in the Canadian Arctic (Figure 3). The CMIP6 SSP5-8.5 projections show an increase of 17 per cent of sea ice concentration loss compared to the CMIP5 RCP8.5. For both ensembles, the Western Arctic and Hudson Bay areas will be the most affected with -40 per cent to -57 per cent sea ice decline compared to the baseline. The region least affected is the eastern Canadian Arctic with a -five per cent to -35 per cent decline. Sea ice concentration loss areas expand with the ensemble results from CMIP6. The expansion occurs from a west to east direction in the Northwestern Sea, and in a north-south and east-west direction in the Hudson Bay area with values ranging from -25 per cent to -45 per cent decline. New areas of loss of sea ice concentration are also observed in the Northwest Passage and the Hudson Strait.

Figure 3. Sea ice concentration (SIC) projections considering IPCC-AR6 SSP5-8.5 and IPCC-AR5 RCP8.5 at the end of the century (2081–2100).



Source: Adapted from CMPI5 and CMPI6.

3. CLIMATE CHANGE CHOKEPOINTS

Climate change, extreme temperatures and precipitation will produce impacts that may hinder the establishment of transportation corridors in northern communities. These impacts can generate chokepoints to the transportation sector, disturbing potential plans for the CNC. The term "chokepoint" used in this study has been widely used in the maritime sector to designate natural congestion along two wider and important navigable passages and was proposed in the context of the CNC by Pearce et al. (2020) as key junctures in transportation and infrastructure systems that are vulnerable to obstruction. It has also been associated with military designation of valleys, defile, bridges or critical waterways such as a strait, which an armed force must pass. "Climate change chokepoints" hereafter concerns any climate, weather or physical feature pattern or event that may obstruct transportation modals flow in the CNC. Our focus on chokepoints in this study reflects the fact that climate change risks will not be equally distributed across the large area covered by the CNC, but concentrated in locations where multiple hazards overlap and which thus impact accessibility across the whole transportation network.

3.1 CLIMATE CHANGE HAZARDS CHOKEPOINT

Climate change hazards chokepoints concern any known or visible weather or physical phenomena such as downpours, blizzards, gale winds, floods, flash floods, landslides, wildfires, erosion, coastal erosion or increased wave energy that may block, destroy or damage routes or transportation infrastructure. Climate-related chokepoints can also be considered as slow onset; for example, the slow thawing of permanent permafrost, the decrease in sea ice thickness, changes in humidity or air temperature patterns. Chokepoints related to fast onsets can include a sudden change in temperatures, causing extreme heat/cold waves and torrential rains falling within hours or a day.

Current and emerging climate change chokepoints will dictate how buildings and transportation infrastructure should be planned. For example, new building codes and costs that incorporate and internalize climate information into infrastructure life cycles will have to be considered while designing the CNC. The Canadian government is tackling some of these concerns by developing adequate standards and codes that incorporate climate change projections information into building standards. A good example includes the ISO requirements from the Standards Council of Canada (SCC), as part of the Northern Infrastructure Standardization Initiative (NISI), that aims to address CC's impact on Canada's northern infrastructure. These standards include infrastructure planning, design, development and management of controlled and uncontrolled risks imposed by climate change (SCC 2020). More on codes and standards for infrastructures can be found in SP-3.

3.2 CHOKEPOINT HOTSPOTS IN NORTHERN CANADA

To map areas with higher risks of climate change-related chokepoints, we have developed a hotspots analysis[8] to a given set of weighted variables using the ArcGIS 10.7.1 Getis-Ord Gi* tool (SP-5). To be a statistically significant hotspot, a feature will have a high value and be surrounded by other features with high values as well. The local sum for a feature and its neighbours is compared proportionally to the sum of all features; when the local sum is very different from the expected local sum, and when that difference is too large to be the result of random chance, a statistically significant z-score results. The Gi* statistic returned for each feature in the dataset is a z-score. For statistically significant positive z-scores, the larger the z-score is, the more intense the clustering of high values (hotspot). For statistically significant negative z-scores, the smaller the z-score is, the more intense the clustering of low values (cold spot) (Getis and Ord 1992; Ord and Getis 1995).

Both hotspots and cold spots are clusters of values for the variable at a certain area. If the cluster is large, it is considered a hotspot; if the cluster is small, it is considered a cold spot. Both hotspot and cold spot areas are prone to create chokepoints, but the area with the larger clusters (hotspot) is the one with most potential impact for the CNC.

We applied this technique considering historical wildfires (> 200 hectares), extreme precipitation in one day (Rx1-day), extreme snowfall in one day (SnowMax1-day) and variables related to melting of permafrost such as thawing degree days (TDD) [degrees] (Cumulative sum of daily degrees of Tmean above 0°C, over a winter-centred year[9]), and snow cover duration (SCD) [days] (the number of days in a winter-centred year with snow depths ≥ two cm). All variables considered (excluding wildfires) are climate projections for 2081–2100. Results of projections were computed for both sets of inputs including

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8 This technique consists of limiting a fixed band distance for each feature analyzed within the context of neighbouring features. Neighbouring features inside the specified critical distance (distance band or threshold distance) receive a weight of one and exert influence on computations for the target feature. Neighbouring features outside the critical distance receive a weight of zero and have no influence on a target feature's computations. Finally, we used Euclidian distance, which is the straight-line distance between two points.

9 A winter-centred year is a year starting on August 1 and ending on July 31 of the next calendar year.

the mean, 10th and 90th percentiles for AR5 RCP4.5, RCP8.5 and AR6 SSP5-8.5 scenarios for sensitivity analysis.

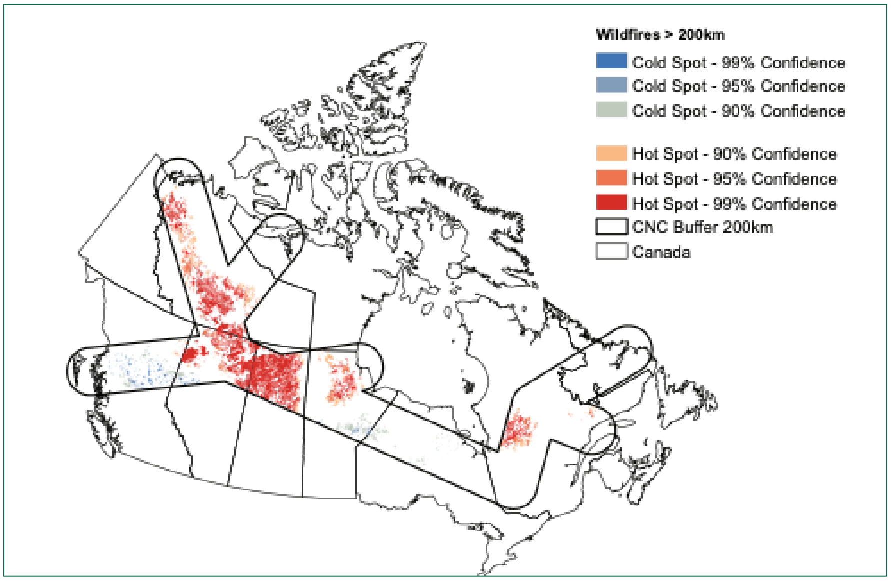
In the next section, we will explore climate change chokepoint examples in northern Canada to understand which weather, climate and physical features conditions may impact the CNC the most. After an expert selection of climate change chokepoints, we will examine construction, operation and maintenance costs for the corridor under future climatic conditions and the potential costs that climate change could have on the corridor.

3.3 CHOKEPOINT EXAMPLES

3.3.1 Alberta and British Columbia – Wildfires

The Fort-McMurray (Alberta) wildfires in 2016 and British Columbia province-wide wildfires between 2017 and 2021 have caused enormous costs to provincial governments, including the loss of lives and livelihoods, extensive private, public property and infrastructure damage, increased health costs related to cardiovascular, respiratory and psychological diseases, and soaring insurance values. A historical assessment of large wildfires encompassing areas of ≥ 200 km published by the Canadian Wildland Fire Information System[10] have been calculated for the entire landmass of Canada. The assessment shows that large wildfires are present along the entire corridor area, especially in forested sites. The hotspot analysis developed in our study indicated that the central and northwestern parts of the corridor are the most critical, with additional patches in the eastern part of the corridor (Quebec region) (Figure 4).

Figure 4. **Large Wildfires ≥ 200 km hotspots. Red tones indicate regions where wildfires have been more concentrated and abundant.**



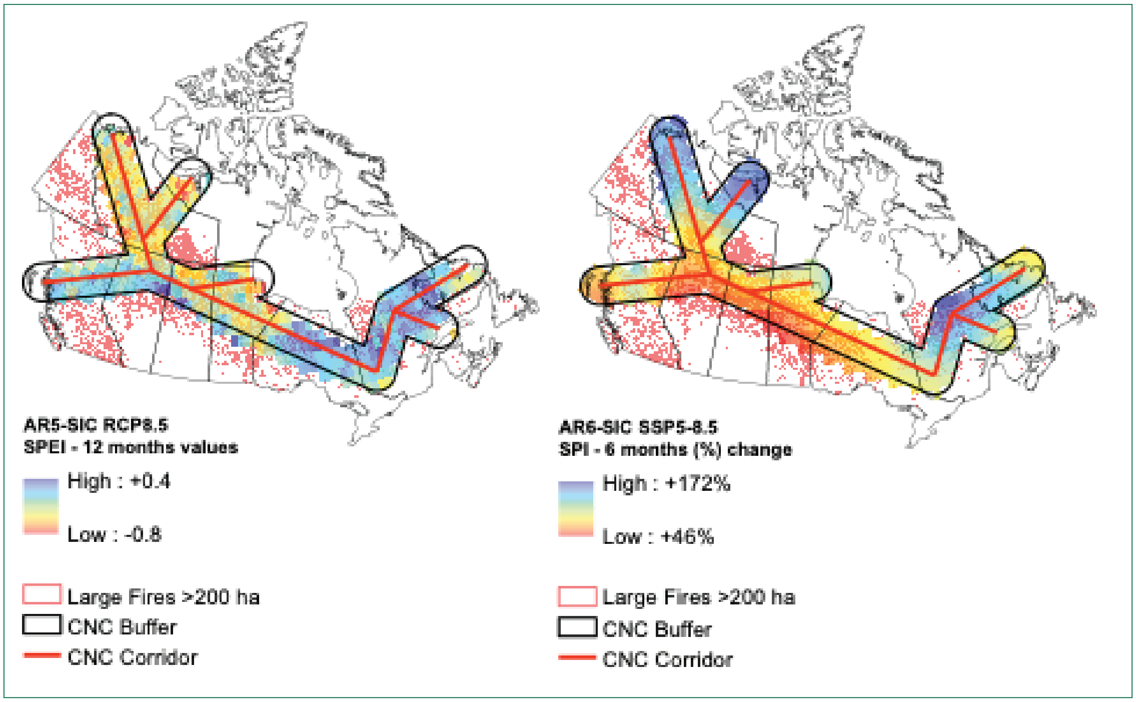
Source: Adapted from the Canadian Wildland Fire Information System.

[10] National Fire Database fire polygon data (large fires only > 200 hectares.

With increasing CC extreme heatwaves, higher maximum, minimum and mean temperatures, and the decrease in humidity and increased drought conditions, it is expected that wildfires will grow larger and more extreme. The SPI-6 and SPEI-12 indices drought analysis from our CC projections section shows major increases in drought patterns in the future, especially in the central and western parts of the corridor. Some increases may surpass the 100 per cent mark (Figure 5).

Wildfires represent a significant threat for the CNC, especially the central and northwestern parts. Wildfires may produce important chokepoints disrupting energy and communication transmission through fire damage to for wires, cables and posts/poles. Wildfires can also affect several transportation modals such as highways, trainways, roads and airports through blockages of passages or decreased visibility due to smoke conditions or the production of lightning strikes and cloud convection. These threats inhibit local and regional traffic and transportation logistics while impeding the access of rescue crews, evacuation or access to goods and services.

Figure 5. SPI-6 SSp5-8.5 and SPEI-12 RCP8.5 values layered on top of large ≥200 km wildfires for the CNC corridor.



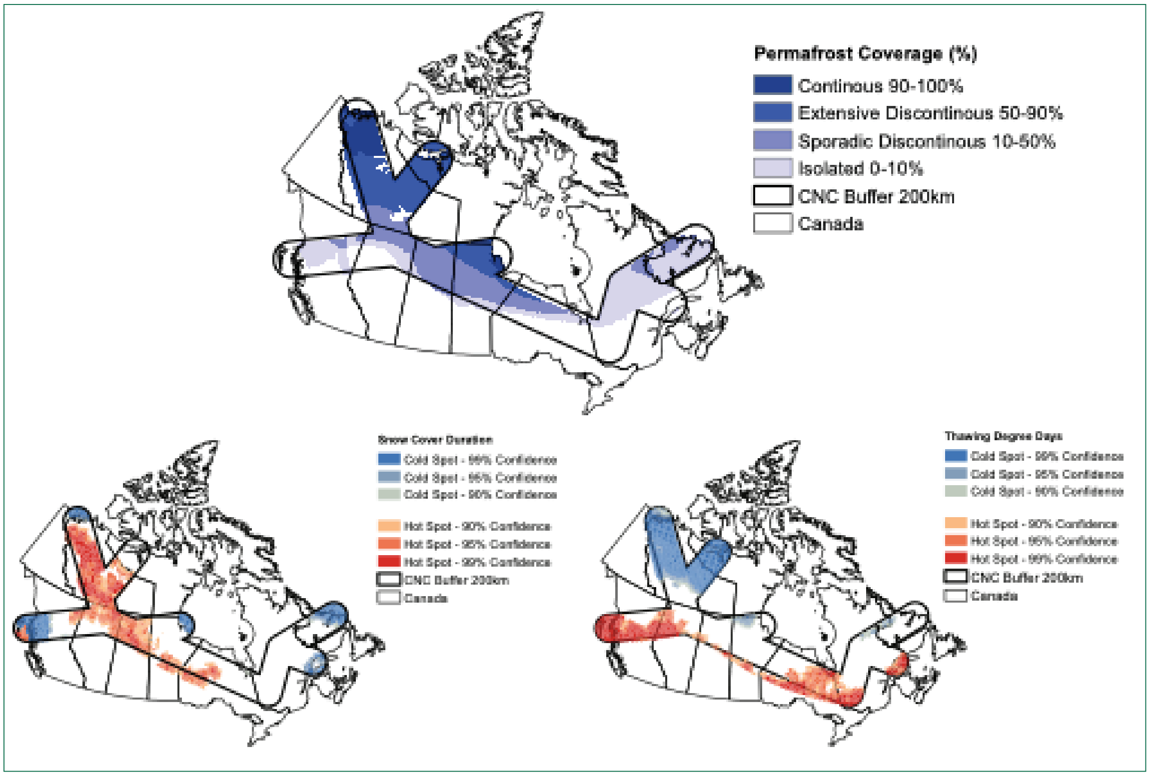
Source: Adapted from CMIP5-6 and the Canadian Wildland Fire Information System.

3.3.2 Permafrost

The CNC area includes all forms of permafrost coverage from contiguous (90–100 per cent) to isolated (zero–10 per cent). More unstable forms of permafrost with an important active layer are localized mostly in the south and eastern parts of the corridor, while the continuous type is secluded to the CNC's most northwestern extreme. As discussed in the introduction, numerous variables can affect changes or loss in permafrost, making it a challenge to model into climate scenarios. Some climate variables and indices can help determine areas that may become more vulnerable to thawing permafrost. For example, permafrost can be affected by snow cover duration and the incidence or recurrence of temperatures above ≥0°C freezing level (Figure 6).

In our hotspot analysis, we assessed snow cover duration (SCD) and thawing degree days (TDD) to identify areas of concern. Areas where SCD is more threatened include the western part of British Columbia and coastal areas in the northwestern and eastern tips of the CNC (which can be rich in sea ice or coastal permafrost). Permafrost areas of greater coverage (per cent) coincide with the coastal areas of the CNC. Currently, permafrost coastal erosion is a well-known problem for communities' infrastructure in northern Canada, damaging livelihoods, ports, airports and public and private properties (Ford, Bell and Couture 2016). With increased CC affecting sea ice extent, thickness and wave energy in coastal areas (rich in permafrost), it is highly likely that coastal erosion of permafrost will increase, demanding higher costs to rebuild, adapt or protect coastlines and buildings. Moreover, the accumulation of drifting ice against the shores will increase damage to permafrost, affecting marinas, ports and other marine infrastructures important for northern transportation inter- and intra-communities. TDD hotspots analysis values were not significant for most parts of the CNC area. However, TDD hotspot analysis is high for the western part of the corridor, which may indicate melting processes occurring with higher frequency in isolated or sporadic discontinuous permafrost areas for this region.

Figure 6. On top, permafrost typology and percentage coverage for the CNC's area. On the bottom left, hotspot analysis for snow cover duration (SCD) and on the right side, hotspot analysis for thawing degree days (TDD) considering the 2070–2100 period for RCP8.5.

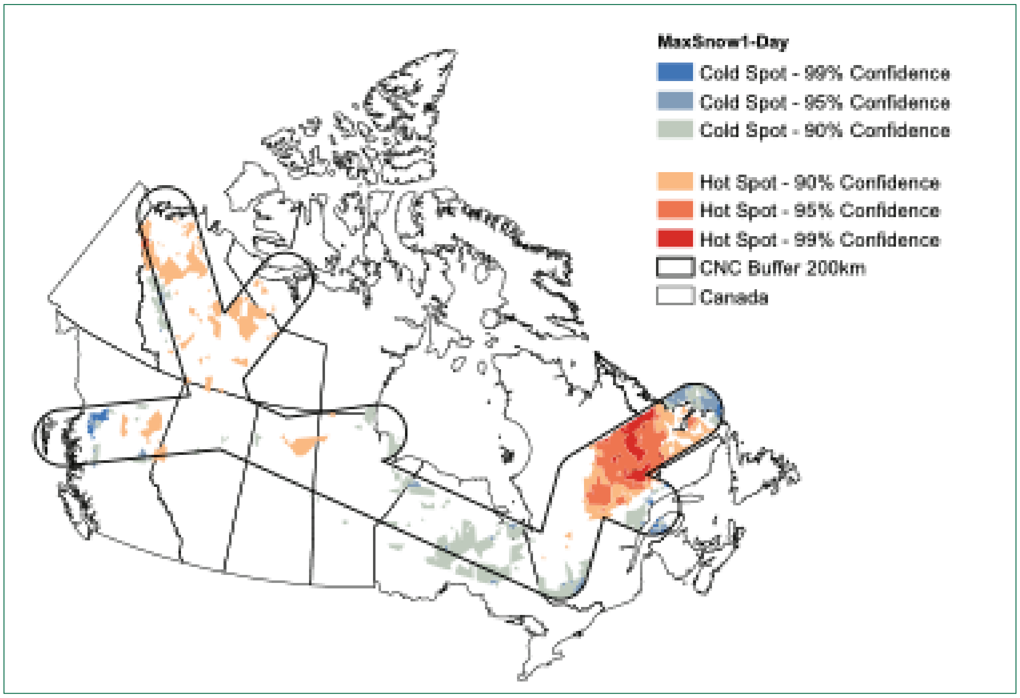


Source: Adapted from Brown et al. (2002) and the CMIP5 CORDEX experiment for the Arctic region.

3.3.3 Alaska – Air Transportation and Extreme Snowfall

In Alaska, small airports have updated their infrastructure technology by incorporating antennas that send signals to aircrafts to allow them to land under blizzard, storms or dense fog conditions. This investment has saved time and money for passengers and cargo travellers, decreasing flight diversion and logistic issues while improving safety. However, increasing blizzard conditions and extreme snowfall episodes have produced extreme snow accumulation which blocks these signals. When snow accumulation on airport runaways becomes too high, antennas cannot provide proper signals back to aircrafts or accurate landing information for pilots and airport staff. Considering that CMIP6 projections indicate an increase in frequency in extreme precipitation patterns, air transportation will need to tackle these extremes and plan for unknown conditions. Hotspot analysis for maximum snowfall in one day for the RCP8.5 during the 2071–2100 period indicates some areas of concern for this variable, especially the eastern and northwestern corridor areas. Quebec and Newfoundland and Labrador will be impacted the most (Figure 7).

Figure 7. Extreme snowfall precipitation hotspots. Red tones indicate regions where extreme snowfall will be more concentrated and abundant. Rx1daySnow = one-day maximum snowfall [mm/day] (annual maximum of daily snowfall for a winter-centred year).

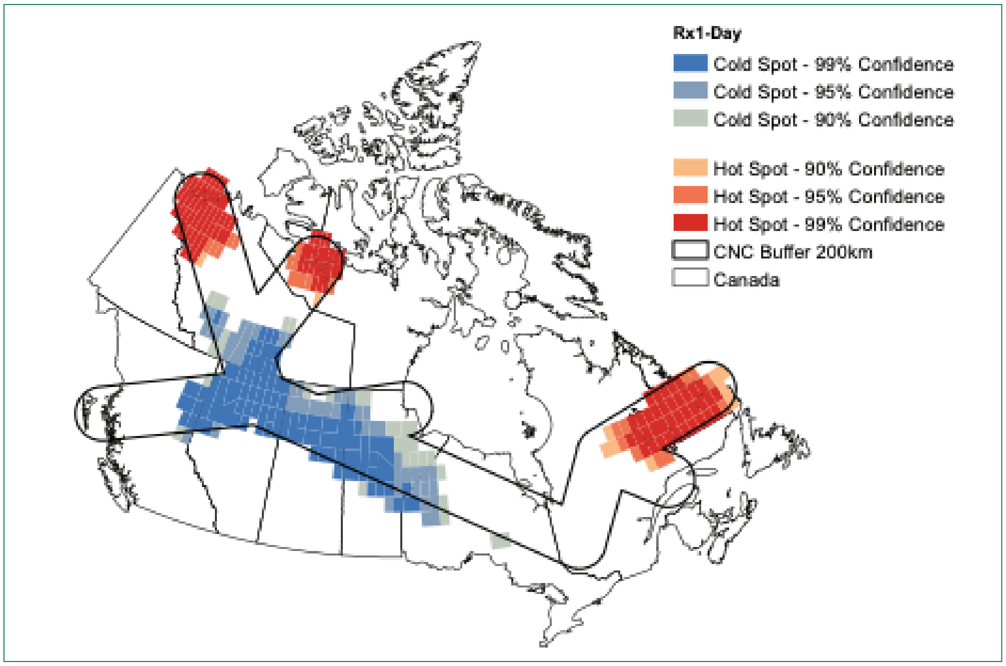


Adapted from the CMIP5 CORDEX experiment for the Arctic region.

3.3.4 Northwest Territories – Road Transportation and Extreme Weather

Northwest Territories inhabitants living in remote communities may travel around 500 km or more once a week to specific locations to acquire their home supplies or groceries. These remote areas often have poor road maintenance and travellers may drive for several hours before finding a gas station or any sort of public or private infrastructure (Figure 8).

Figure 8. Extreme rainfall precipitation hotspots. Red tones indicate regions where rainfall extreme precipitation will be more concentrated and abundant. Rx1day = annual maximum one-day precipitation [mm/day] (annual maximum of daily precipitation).



Adapted from the CMIP5 CORDEX experiment for the Arctic region.

Travellers often rely on good weather forecasts to avoid dangerous blizzard or ice conditions on roads; however, these forecasts often do not provide a high accuracy at the local level. Therefore, in the case of a car failure, road accident or being caught up in a weather-related accident, only a few resources would be available (i.e., cellphone, radio and road assistance phones). Furthermore, due to the remoteness of these territories, rescue during extreme weather may take too long to arrive, increasing the severity of injuries or possible loss of lives. CC will increase frequency of blizzards, ice storms, wildfires and landslides/avalanches, with greater risk for these travellers. Maximum rainfall precipitation in one day hotspot analysis indicates that the northwest and the eastern parts of the corridor will be most impacted.

3.3.5 Ontario and Quebec – Ice Storms/Freezing Rain

Of all Canadian hydrometeorological hazards, freezing rain is associated with the highest damage costs per event. This hazard can affect wind energy generation (Yang et al. 2015), urban functioning (Hauer et al. 2011; Armenakis and Nirupama 2014), communications (Mulherin 1998), forestry (Proulx and Greene 2001; Seidl et al. 2017) and electrical infrastructure (Fu et al. 2006; Rezaei et al. 2016; Jeong et al. 2018). CC projections indicate that warming temperatures will increase the occurrence of freezing rain events in northern Canada. By the 2080s, freezing rain events could increase by 45–135 per cent during the colder months (December-February) in southern–northern Quebec, Ontario and Manitoba. The increase in the number of daily freezing rain events for the coldest months is projected to be progressively greater from south to north or from southwest to northeast across eastern Canada (Cheng et al. 2007, 2011).

Increases in ice accretion (caused by freezing precipitation during ice storms) for latitudes higher than 40°N are substantial (+35 per cent) and at 60°N project changes can reach more than +100 per cent (Figure 9a,b). These changes have significant implications for building and infrastructure design for northern communities (Jeong et al. 2019). Projected changes[11] to extreme ice loads[12] foresee an increase in future design ice loads for most of northern North America, decreases for most of southern North America and for some northeastern coastal regions. Changes in ice loads are mainly caused by regional increases in future upper-level surface temperatures associated with global warming (Jeong et al. 2019). According to Jeong's study, freezing precipitation (FP) occurrence hours can increase to more than 50 per cent for some of CNC's regions. The areas most impacted include the central parts of the corridor and the northwestern and western regions (Figure 9c). This increase in FP occurrence hours is extremely concerning for transmission lines, meaning that a long ice storm may cause extensive damage to transmission line infrastructure throughout the entire CNC area.

Smaller decreases in FP occurrence hours between 20–30 per cent will occur in the eastern part of the corridor for short-term FP events, but new studies show that long-term FP events seem to increase in percentage over time (Marinier et al. 2022).

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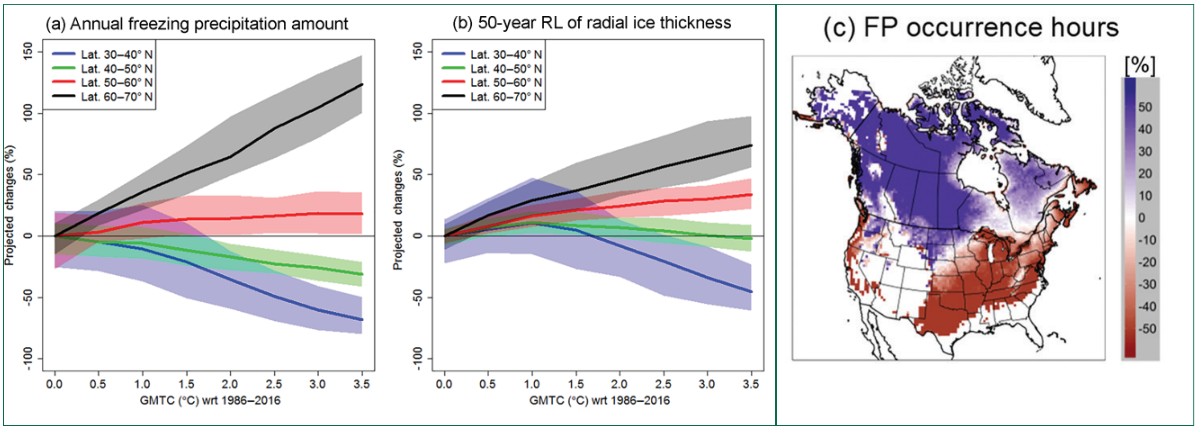
11 From CanRCM4 regional climate model, driven by CanESM2 under the RCP8.5 scenario.

12 Used to design infrastructure over North America.

Figure 9. Zonal means of projected changes in the CanRCM4 large ensemble to annual FP amount (a) and 50-year RL radial ice thickness (b) for four different latitude zones (i.e., 30–40, 40–50, 50–60 and 60–70°N latitudes) over North America, as a function of global mean temperature change (GMTC) relative to the baseline period. Minimum and maximum values of areas and lines represent fifth and 95th percentiles and median values, respectively, obtained from the ensemble (c) freezing-precipitation (FP) occurrence hours from the CanRCM4 large ensemble at +2°C GMTC level with respect to the baseline period.

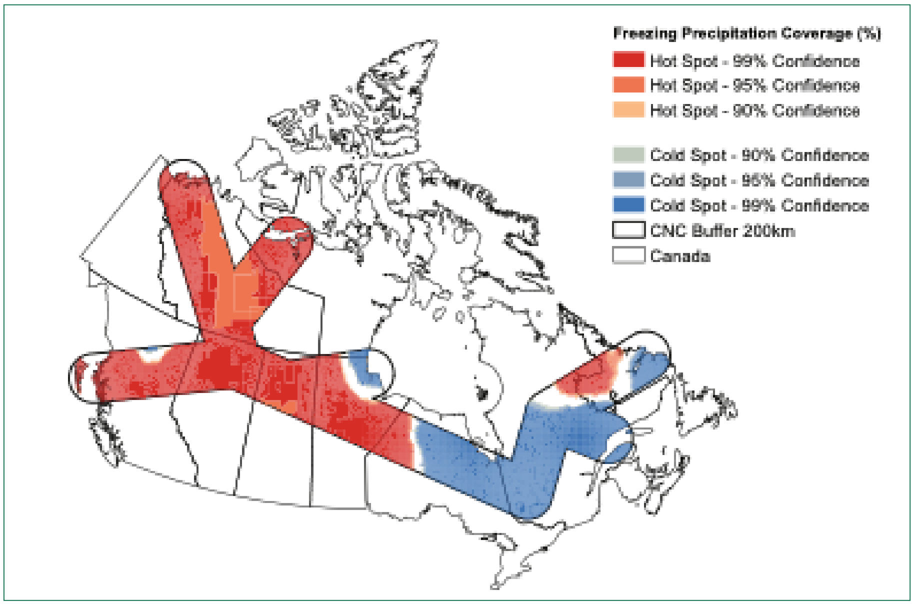


Source: Adapted from Jeong et al. (2019).

The FP coverage hotspot analysis in Figure 10 indicated that the most concerning area for the corridor includes the central, western and northwestern regions. Some FP concerning spots are also seen in the eastern side, including eastern Quebec and Maine (Marinier et al. 2022). Though the cold spots regions will also see increases in FP, the magnitude will be smaller. It should be noted, however, that the eastern side of Canada is more commonly affected by strong ice storms; for example, the 1998 major event in the St. Lawrence valley (Nicolet 1999).

The CNC should carefully consider the feasibility of infrastructure development, especially in the telecommunications sector, air and rail transportation. Major chokepoints can happen due to ice accretion creating logistic issues at airports with flight delays, dangerous road conditions, cuts in electricity due to ice accumulation in electrical lines and loss of power, energy and heating sources for livelihoods and private and public businesses.

Figure 10. Freezing precipitation (FP) hotspot analysis calculated for the CNC considering RCP8.5.



Source: Adapted from Jeong et al. (2019) – CanRCM4 large ensemble at +2°C global mean temperature change (GMTC) level with respect to the baseline period.

3.3.6 Manitoba – Floods

Floods are the most frequent, and currently the most expensive hazard in Canada. By 2050, floods are expected to cause 38 per cent of the economic impacts in the country (GHD 2022). Floods are caused by heavy rainfall, rapid melting of a thick snowpack or ice jams (Government of Canada 2022). One of the most flood-prone areas in Canada is located along the Red River in Manitoba. The region has extreme weather variations, and flooding occurs due to several coupled factors such as the sudden thaw of snowfall, heavy precipitation or melting snow during spring's ice break-up. During the 1974–1997 period, the Canadian government spent more than $229 million in federal payments under disaster financial assistance arrangements for floods in Manitoba (Government of Canada 2022).

In the CNC areas, projections from CMIP5 RCP8.5 /CMIP6 SSP8.5 ensembles show that extreme rainfall events between one and five days will increase between 40–50 per cent by the end of the century. With increased temperature and intense precipitation in an unstable climate, Manitoba and other regions of the CNC are expected to endure greater flood hazards in frequency and intensity. In 2022, a combination of melting snow and persistent storms and rainfall caused $200 million worth of damage in Manitoba, with lakes and rivers rising, resulting in major overland flooding, falling just short of a worse disaster in 2011 (CBC News 2011; 2022).

3.4 CHOKEPOINTS SYNTHESIS

These chokepoint examples serve as an important question mark on how the CNC expects to address infrastructure remoteness, maintenance and costs associated with having a transportation corridor in such remote area. To capture how the amalgamation of these chokepoints will impact the CNC, we combined the hotspot layers for nine variables including large wildfires; spi6 and spei12 drought indices; maximum snowfall in one day; maximum precipitation in one day; snow cover duration; thawing degree days; permafrost; and freezing precipitation. These nine layers were combined by normalizing values using a zero-to-one scale, with zero representing the areas least concerning for the chokepoints and one the areas concerning the most.

These calculations were performed using the map algebra tool in ArcGIS 10.7.1.
The normalization used a simple equation:

$$x_{norm} = \left(\frac{x - x_{min}}{x_{max} - x_{min}}\right)$$

Where x_{norm} represents the mean value for the variable (raster file), x_{min} the lowest and x_{max} the highest grid value.

The calculations indicated that the chokepoints accumulation is most important in the CNC's central region (Figure 8). Mean values are higher for Saskatchewan, Alberta and Manitoba, but the areas of maximum values are mostly in the Northwest Territories and Manitoba (Table 2). From this analysis, we can conclude that these regions will likely have a higher probability of receiving concomitant impacts of several chokepoints which would increase costs for infrastructure and transportation. The region is also located in the centre area of the west–east flow of the CNC.

From this perspective, we believe that a cost analysis should be conducted focusing on important transportation or infrastructure hubs that function as communication and connecting points to the CNC. Given the current findings and the geographical distribution of results, we believe that MB, BC, AB and NT would work as representative case studies in terms of distribution centres and points of major infrastructure for the distribution of goods and services in the region. Therefore, our cost analysis related to CC chokepoints will scrutinize these specific regions.

We did not consider Saskatchewan as part of the analysis since the northern parts of the province did not include substantiated data on infrastructure. Once data are available, this province should be explored with priority since it scored the highest value in our analysis.

Figure 11. Map showing the chokepoints accumulation values between zero and one for the CNC buffer areas. The higher the value, the higher the accumulation of chokepoints in each region.

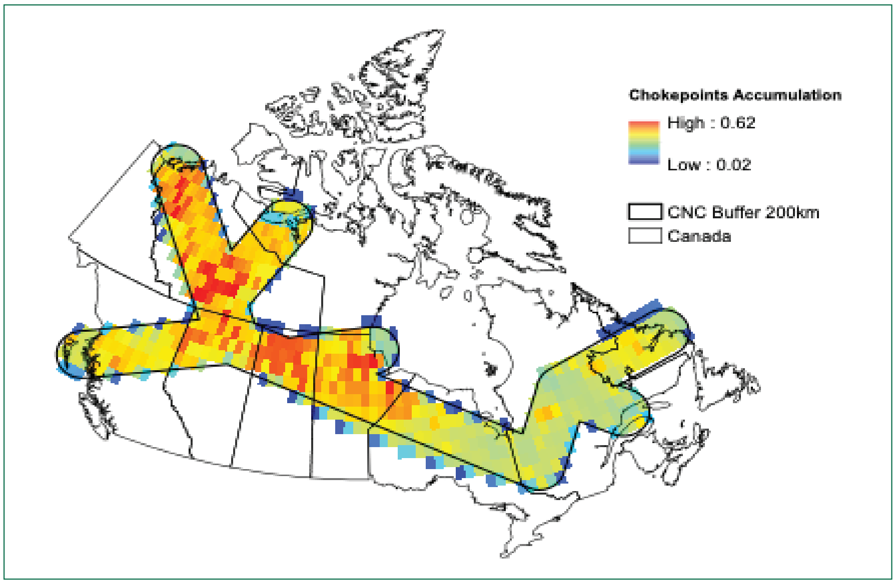


Table 2. Chokepoints accumulation values between zero and one for the CNC buffer areas. The higher the value (warm colours), the higher the accumulation of chokepoints in each region.

	Chokepoints Accumulation 0-1		
Area	**Min**	**Max**	**Mean**
Saskatchewan	0.03	0.58	0.47
Alberta	0.25	0.58	0.46
Manitoba	0.06	0.60	0.45
Northwest Territories	0.08	0.62	0.43
British Columbia	0.10	0.51	0.39
Nunavut	0.09	0.50	0.39
Yukon Territory	0.22	0.52	0.39
NF and Labrador	0.12	0.47	0.37
Ontario	0.02	0.51	0.34
Quebec	0.11	0.48	0.34

4. CLIMATE CHANGE COSTS CALCULATION ON INFRASTRUCTURE

Cost calculation on infrastructure is a vast subject including several available methods to determine the implementation of projects specific to regions, types of materials and the life cycle of structures. For the CNC analysis, we narrow our discussions and methods to focus on transportation, energy transmission (including telecommunications) and buildings infrastructures pertinent to the corridor area. Beyond the normal cost calculation for infrastructure, this study adds a CC cost component considering the CNC regions. The intention is to capture how costs can be exacerbated or decreased depending on future CC conditions in the corridor. This can help determine the corridor's implementation feasibility in certain areas. Therefore, to explore and synthesize the literature we focus on studies and methods that have assessed CC costs on roads, telecommunications, railways and ports/coastal infrastructures. In the following sections, we analyze these methodologies and select the ones most appropriate to the CNC study. Since a vast majority of these methods used datasets that may not be available for the CNC area, we had to dissect methodologies that would be a best fit for our study needs and data availability. Whenever possible, we scoped CC costs on infrastructure considering polar regions.

At a screening level, CC cost analysis on infrastructure usually follows a four-pillars structure (Schweikert et al. 2014; Fant et al. 2020; Neumann et al. 2021). This structure includes a) collecting inventory data available for the infrastructure type; b) collecting CC data, including scenarios and climate variables; c) the development of stress-response functions to relate climate stressors to the response of various relevant infrastructure components; and d) governance planning scenarios responses (adaptation responses) that include a business-as-usual approach (no action is taken to reduce emissions or adapt to CC), reactive (action is taken after certain tipping points are reached) and proactive (planning and action are done in advance, even if CC may not occur). Adaptation measures are particularly important when considering the long-lived nature of infrastructure. Temperature and precipitation changes projected after 2050 mean infrastructure built today needs to be designed to remain functional under a different climate future than what we experience now (Fant et al. 2020).

In addition to this four-pillar structure, CC infrastructure cost studies tend to focus on: 1) costs calculation related to the life cycle of structures, including materials tear and deterioration, and 2) the costs associated with the disruption of flow of people, goods and services. But studies can also focus only on one of these elements. Cost calculation approaches often include engineering methods and frameworks. To see a literature review on these approaches including roads, energy transmission and telecommunications, railways, ports and coastal infrastructure worldwide and on polar regions, please consult SP-5.

4.1 METHODS

4.1.1 Framework of Analysis

To calculate CC costs for the CNC area including transportation, energy transmission/telecommunications and built infrastructure, we use a mixed method approach following the four-pillar framework based on the studies developed by Neumann et al. (2021), Fant et al. (2020), Suter et al. (2019), Hjort et al. (2018) and Schweikert et al. (2014) (Figure 12). We adapt our CC cost analysis according to the availability of infrastructure inventory data for the CNC area and for the specificities of polar and subpolar regions. In this study, we calculate CC direct costs on infrastructure life cycles (repair). The data used in this study include a) Canadian inventory infrastructure information for nine sectors, and b) climate variables and climate extreme indices for CMIP5 (RCP8.5) and CMIP5 (RCP4.5) with median, 10th and 90th percentiles and CMIP6 (SSP5-8.5) median percentile for sensitivity analysis.

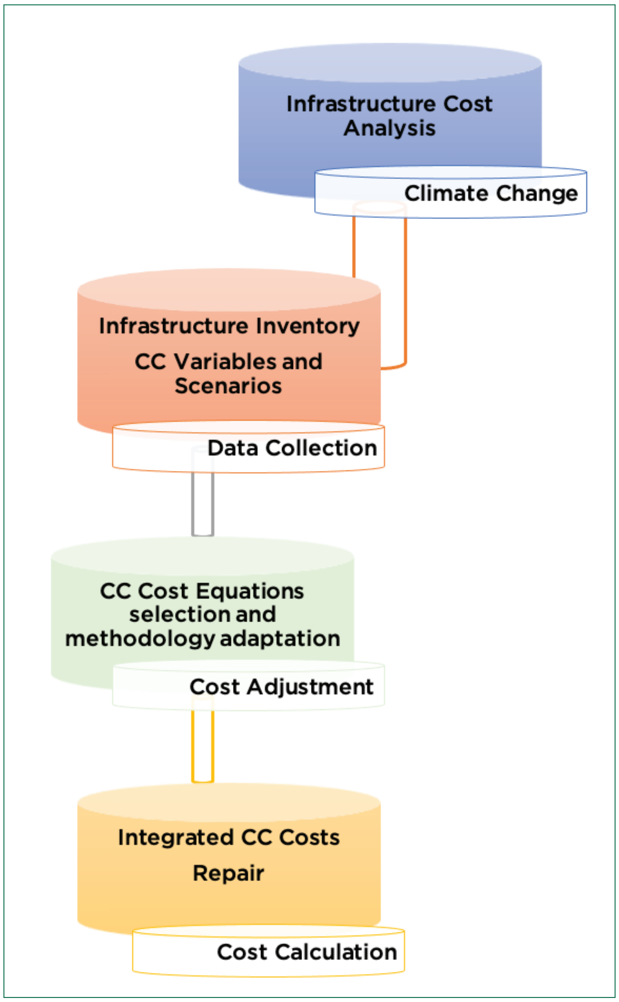
Moving a step ahead from the previous studies, our work integrates CC costs from the three different sectors with direct costs which often produce tradeoffs; for example, minimizing adaptation costs may risk increasing user costs. We also explore beyond the common temperature and precipitation variables including wildfires, permafrost and extreme climate indices. The nine sectors under our analysis function as an integrated system of demand and mobility for people and goods to maintain economic viability; therefore, it is important to consider an integrated view of these costs (Sun et al. 2020; Neumann et al. 2021).

In the sections below we describe the methods used to:

1. Collect, process and analyze available infrastructure inventory data for the nine sectors;
2. Select and adapt costs calculations for climate stressor conditions for nine infrastructure sectors including repair (direct cost);
3. Calculation of the climatic cost for nine sectors and including CMIP5 RCP4.5 and RCP 8.5, including 10th and 90th percentiles and CMIP6 (SSP5-8.5) for sensitivity analysis; and
4. Integrate nine sector cost results under a final CC infrastructure cost analysis.

Data collection such as Canada's infrastructure inventory on investments, stock and other datasets useful for this analysis can be found in SP-6.

Figure 12. CC Infrastructure Cost Analysis Framework.



4.1.2 Costs Calculation

To calculate CC impacts on costs, we first need to develop, reproduce or adapt cost calculations for different infrastructure types. Infrastructure suffers common direct impacts (repair) during its life cycle from normal tearing or decay of materials. CC creates a new layer of impact to this normal decay, increasing both the direct and the indirect impacts (delay) on populations that use these infrastructures. To understand holistically the different costs of these infrastructure life cycles and their decay, we searched the literature and adapted cost calculations according to previous studies (Neumann et al. 2021; Fant et al. 2020; Schweikert et al. 2014; Diesel 2011, 2012; Perpiñan et al. 2011; Gartner 2008; IPEA 2006; Penatti-Filho 2006; Bonachea 2006). We focused our literature search and cost calculations on studies that have considered buildings, roads, railways, telecommunications and seaports/coastal infrastructures and CC impacts in North America, Europe and South America. So far, the literature considering CC impacts on infrastructure has enough direct impacts costs that we could use and on which we base our equations adaptations. On the other hand, the literature related to indirect CC impacts on populations, delay and intangible costs is still somewhat absent; further research should emphasize and explore these two segments.

After calculating the costs using selected and adapted methods, we add the CC information baseline and future scenarios to calculate the impact of CC on direct costs dependent on data availability. We finally integrate direct costs considering CC scenarios to understand the total cost of CC impact on infrastructure in the CNC area. These costs vary depending on present time values (baseline) and the impact of several CC variables on the CMIP5, RCP8.5, RCP4.5 and CMIP6 SSP5-8.5 scenarios.

4.1.3 Formula Adaptation

CC costs were calculated as a pilot project including data on Alberta, British Columbia, Manitoba and the Northwest Territories. These provinces were selected because they scored the highest accumulative and mean values in the CC hazards' chokepoints accumulation score. CC data including baseline and scenarios variables were calculated to consider solely mean values, 10^{th} and 90^{th} percentiles within the CNC area for the four provinces. Infrastructure investment costs had to consider the full area of the four provinces since we were unable to dissect to the CNC buffer areas. CC and investment costs variables values are available within an Excel sheet in supplementary materials.

1. At this stage, we analyze costs at a higher screening level using Larsen et al.'s (2008) formula with adaptations to our data gaps (see Larsen's paper for more details on these methods). This formula basically consists of a baseline case and climate change scenario such as illustrated below.

Figure 13. CC cost calculation formula from Larsen et al.'s (2008) work.

r = Real Discount Rate

i = Year

j = Infrastructure Type

Base Case	***Climate Change***
$\theta_j = \dfrac{\text{Replacement Cost j}}{\text{Basecase Useful Life}_j}$	$\Delta_j = \dfrac{\text{Replacement Cost}_j}{\text{Adjusted Useful Life}_j}$
$PV_{\text{Base}} = \sum_{j=1}^{20}\sum_{i=2006}^{2030} \dfrac{\theta_j}{(1+r)^{i-2006}}$	$PV_{\text{Climate Change}} = \sum_{j=1}^{20}\sum_{i=2006}^{2030} \dfrac{\Delta_j}{(1+r)^{i-2006}}$

$$\boxed{\Phi_{2030} = PV_{\text{Climate Change}} - PV_{\text{Base}}}$$

Φ_{2030} = Additional Public Infrastructure Replacement Costs from Climate Change

In our case, instead of using infrastructure replacement costs, since they were unavailable for these provinces, we used the infrastructure mean investment costs (Table 3) for the 2016–2020 period (historical mean of cost during this year). For the useful life variable, we used the infrastructure remaining useful life available for several infrastructure sectors in Canada. For the screening high-level analysis, we selected nine sectors and their structures that seemed important in terms of CNC and chokepoints: 1) commercial buildings;

2) communications networks; 3) electric power infrastructure; 4) institutional buildings; 5) marine engineering infrastructure; 6) oil and gas engineering construction; 7) other machinery and equipment; 8) transportation engineering infrastructure; and 9) transportation machinery and equipment. The analysis of these datasets is available in SP-6.

For the discount rate, we used the three per cent rate which has been applied in several works in this segment and is compatible with Canada's discount rates in 2020. Climate data were added at future climate cost calculations to account for the adjusted useful life and the influence of the variables on infrastructure. CC data acted as the exponential operator in the formula. But before using the climate variables and scenarios in the formula, we calculated the mean and the standard deviation and standardized the series values for normalization. In this step, we also added the chokepoints accumulation scores as an exponential operator for a stand-alone analysis without considering CC. Finally, we calculated the difference in future CC costs minus the baseline scenario to check the percentage increase.

Table 3. Historical Annual Mean of Investment Costs During the 2016–2020 Period in Millions of Canadian Dollars

	Historical annual mean of investment costs (2016-2020) $M				
Sectors	**AB**	**BC**	**MB**	**NT**	**Total**
Commercial buildings	$ 472	$ 477	$ 59	$ 16	$ 1,024
Communications networks	$ 500	$ 575	$ 147	$ 19	$ 1,242
Electric power infrastructure	$ 1,901	$ 2,995	$ 1,796	$ 39	$ 6,730
Institutional buildings	$ 2,370	$ 1,990	$ 465	$ 97	$ 4,923
Marine engineering infrastructure	$ 32	$ 574	$ 17	$ 1	$ 625
Oil and gas engineering construction	$ 1,809	$ 677	$ 32	$ 4	$ 2,522
Other machinery and equipment	$ 241	$ 79	$ 51	$ 6	$ 376
Transportation engineering infrastructure	$ 3,642	$ 2,652	$ 872	$ 126	$ 7,293
Transportation machinery and equipment	$ 254	$ 331	$ 66	$ -	$ 651

5. RESULTS

5.1 DISCOUNT RATE

The discount rate was used to determine the present value of future cash flows in a discounted cash flow (DCF) analysis. This helps determine if the future cash flows from a project or investment will be worth more than the capital outlay needed to fund the project or investment in the present. When applying a discount rate of three per cent on the mean investment costs using Larsen's (2008) adapted base formula, we have the following result values in Table 4. The discount rate shows a substantial decrease in values, as expected. Hereafter, we consider these values to calculate the other steps of our analysis.

Table 4. Mean Investment Costs (2016–2020) in Millions of Canadian Dollars Using the Three Per Cent Discount Rate in Larsen's Formula

	Discount Rates 3% $M				
Sectors	**Alta**	**BC**	**MB**	**NT**	**Total**
Commercial buildings	$ 118	$ 119	$ 15	$ 4	$ 256
Communications networks	$ 125	$ 144	$ 37	$ 5	$ 311
Electric power infrastructure	$ 475	$ 749	$ 449	$ 10	$ 1,683
Institutional buildings	$ 593	$ 498	$ 116	$ 24	$ 1,231
Marine engineering infrastructure	$ 8	$ 144	$ 4	$ 0	$ 156
Oil and gas engineering construction	$ 452	$ 169	$ 8	$ 1	$ 631
Other machinery and equipment	$ 60	$ 20	$ 13	$ 1	$ 94
Transportation engineering infrastructure	$ 911	$ 663	$ 218	$ 32	$ 1,823
Transportation machinery and equipment	$ 63	$ 83	$ 17	$ –	$ 163

5.2 CHOKEPOINTS

The next results concern the stand-alone analysis using the chokepoints results, which includes the chokepoints accumulation points mean scores for the CNC analyzed areas (Table 5). In this analysis, we included the chokepoints as an exponential operator to the infrastructure sectors. The chokepoints calculations including the discount rates of three per cent add substantially to the baseline mean investment costs. Thus, adding a climatic layer to the infrastructure investment costs increases these by +101 per cent. The transportation engineering infrastructure (+100 per cent), the electric power infrastructure (102 per cent) and the institutional buildings (101 per cent) sectors are to be most impacted. The accumulated chokepoints themselves do not alter the order of the higher costs per sector, but they increase overall costs.

Table 5. Chokepoints' Accumulation and Mean Investment Costs Using a Three Per Cent Discount Rate

	Chokepoints with DR3% $M				
Sectors	AB	BC	MB	NT	Total
Commercial buildings	$ 226	$ 255	$ 28	$ 8	$ 518
Communications networks	$ 240	$ 308	$ 71	$ 9	$ 628
Electric power infrastructure	$ 912	$ 1,605	$ 861	$ 18	$ 3,396
Institutional buildings	$ 1,137	$ 1,067	$ 223	$ 45	$ 2,471
Marine engineering infrastructure	$ 16	$ 308	$ 8	$ 1	$ 332
Oil and gas engineering construction	$ 868	$ 363	$ 15	$ 2	$ 1,248
Other machinery and equipment	$ 115	$ 42	$ 24	$ 3	$ 185
Transportation engineering infrastructure	$ 1,747	$ 1,421	$ 418	$ 58	$ 3,645
Transportation machinery and equipment	$ 122	$ 177	$ 32	$ -	$ 331

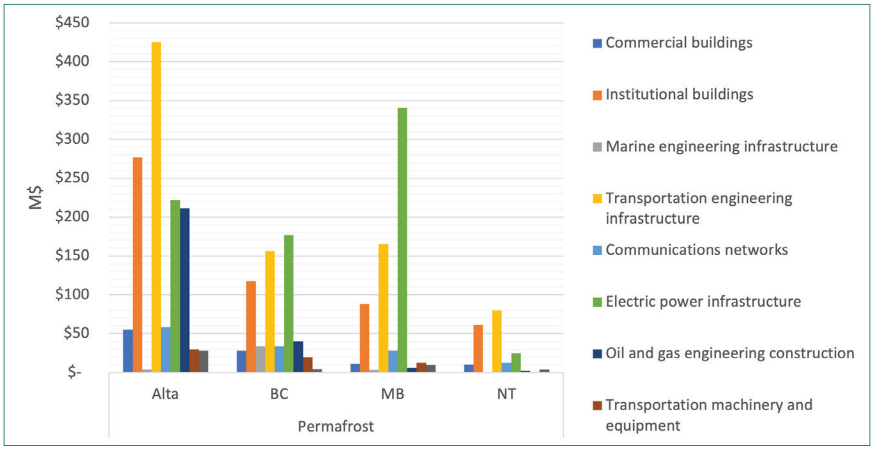
5.3 BASELINE

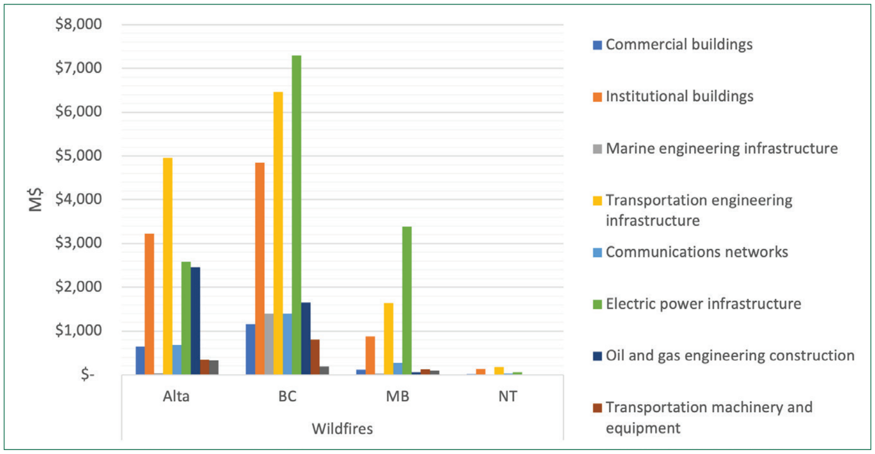
This is a rough CC cost estimate considering that new infrastructure would be built in the CNC's buffer areas. It is worth remembering that much of the CNC's area is not inhabited as indicated in the CNC's population map (SP-6). The following baseline results include nine infrastructure sectors and three hazards (permafrost, fires and freezing rain) with no climate scenario analysis.

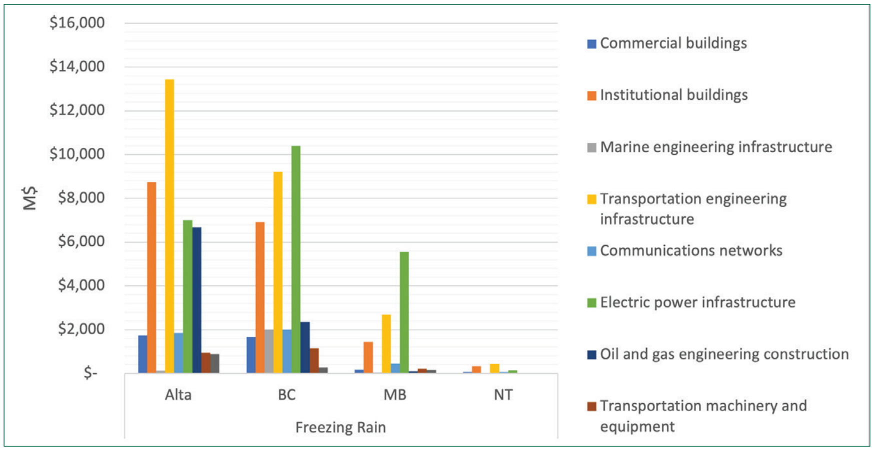
Costs at the baseline are higher when we add the climate lenses (Figure 14). For example, costs soar more than $12 billion when freezing precipitation impacts are added to normal infrastructure costs (especially AB and BC), more than $7 billion for wildfires (especially BC) and more than $400 million for permafrost (especially BC and AB). Results for each sector are available in an Excel spreadsheet as supplementary materials.

One should be careful while considering these values since one of this study's major limitations is that we did not have accessible infrastructure investment costs at a district or regional level to delimit perimeter analysis (for example, for a municipality). A finer scale would provide more accurate results, especially for the permafrost analysis in the Northwest Territories and British Columbia.

Figure 14. Cost Values for Baseline Variables Including Permafrost, Fires and Freezing Precipitation in the CNC's Area in AB, BC, MB and NT.







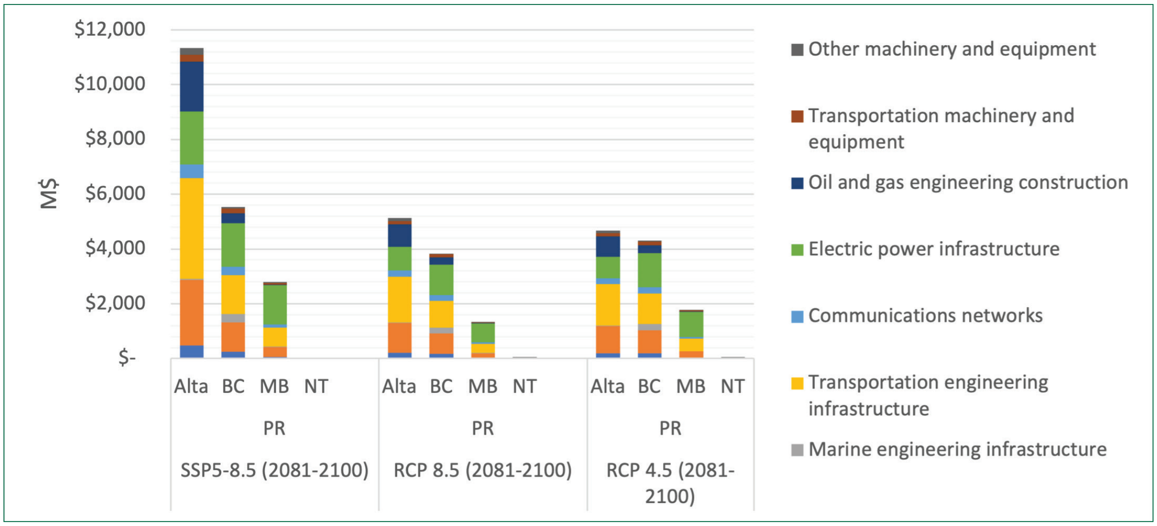
5.4 PROJECTION SCENARIOS

CC scenarios projections and cost results for both CMIP5 and CMIP6 are represented in Figure 15. The figures represent the climate variables cumulative costs in the SSP5-8.5, RCP8.5 and RCP 4.5 projection scenarios at the end of the century. Costs for all provinces and sectors are available in the SP Excel spreadsheets. Note that only precipitation, temperature and thawing degree days variables were considered for the final cost analysis. If we consider the accumulated costs of all infrastructure sector for these variables, we can highlight the following findings:

- AB and BC have the highest accumulated cost (all sectors) for all variables; these provinces have the most infrastructure assets. BC has higher costs compared to AB considering the CMIP6 temperature data. AB has higher temperature values when considering the CMIP5 values. In general, CMIP6 climate variables show a higher degree of change for most climate variables if compared to CMIP5 data. Accumulated costs related to mean temperature for all sectors can reach an additional $40 billion to $15 billion by the end of the century; for TX an additional $45 billion to $15 billion and TN an additional $40 billion to $15 billion, depending on the province.

- Thawing degree days seem to have a larger impact for RCP4.5 compared to more extreme scenarios. This happens because TDD changes become less pronounced in the future with higher warming, with most areas not showing abrupt changes anymore. This is a good indication that permafrost issues will become a major problem even with a conservative scenario. In the case of TDD, BC areas will be the most impacted followed by AB. These permafrost-related impacts are the highest cost increases up to an additional $200 billion to $600 billion (including all sectors), considering that no adaptation options are put in place by the end of the century.

- Precipitation data indicate an increase in precipitation-related costs. Mean precipitation-related costs will be most important for Alberta with an additional $5 billion to $11 billion with direct accumulated infrastructure costs. These costs become much higher if we consider five-day precipitations with an additional $6 billion to $17 billion in direct costs. Five-day precipitation values are commonly attributed to flooding episodes. A decrease in these flooding episodes should occur in the most extreme scenario due to general decreases in precipitation at the end of the century. One-day precipitation values indicate direct costs for all sectors from $6 billion to $8 billion. In the case of one-day precipitation, the Manitoba figure indicates a much higher increase in costs if compared to mean precipitation and five-day precipitation.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Transportation machinery and equipment
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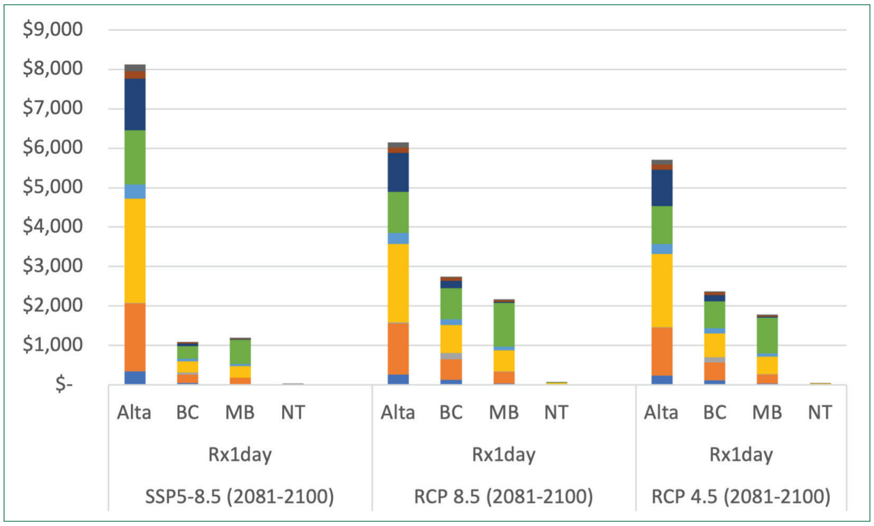
Electric power infrastructure
Communications networks
Transportation engineering infrastructure
Marine engineering infrastructure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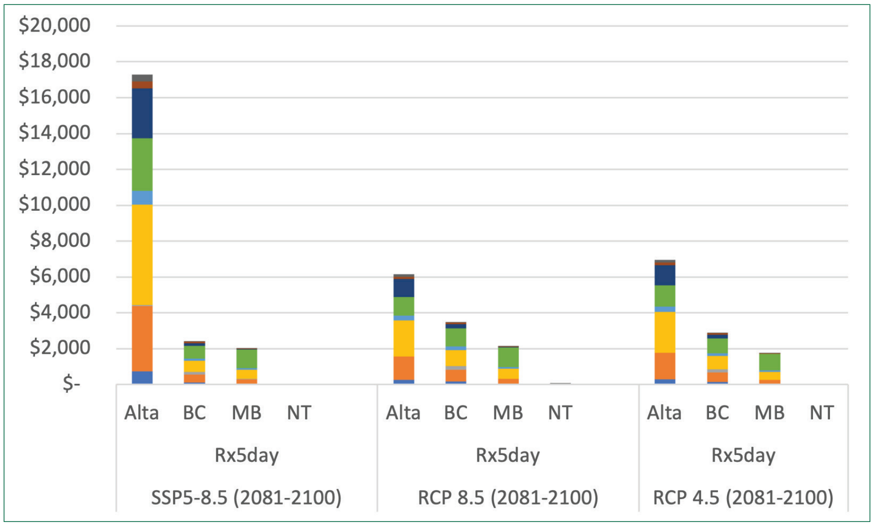
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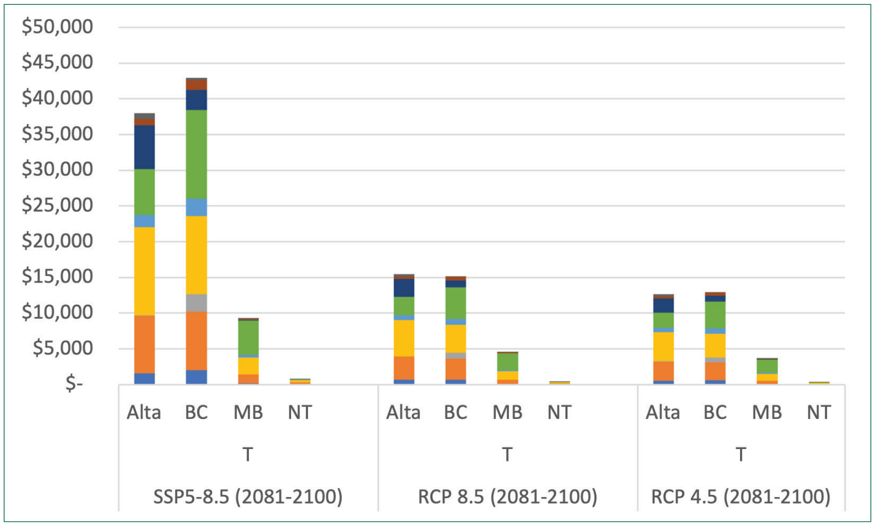
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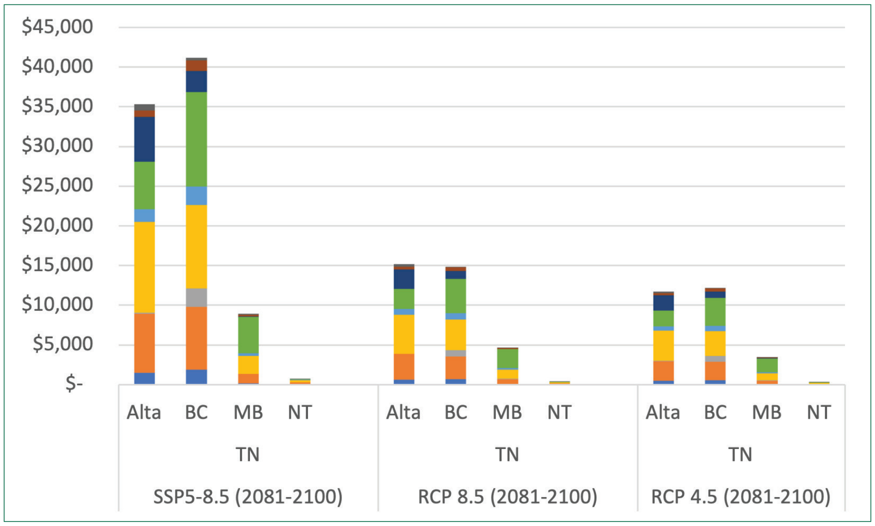
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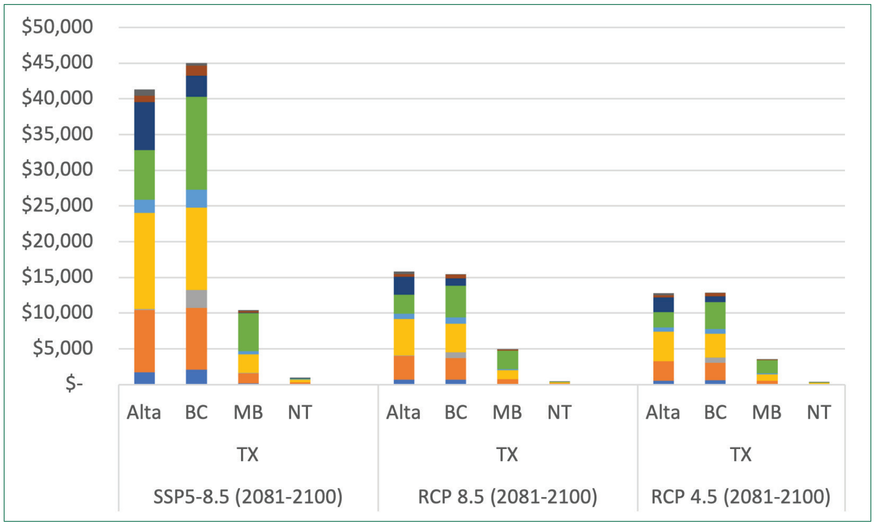
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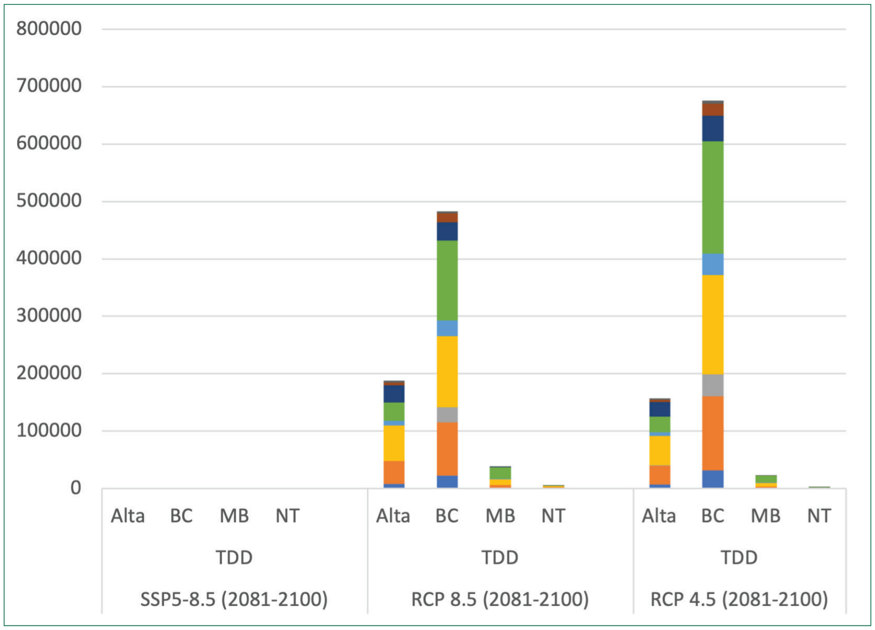

Cumulative costs per sector and per variable indicate the following findings:

- Thawing degree days, maximum temperature and mean temperature will cause the highest direct accumulated costs for all scenarios and provinces. Sectors where costs will be higher in order of costs are a) transportation engineering infrastructure; b) electric power infrastructure; c) institutional buildings; and d) oil and gas engineering construction. For example, considering the CMIP6 values for the end of the century for transportation engineering infrastructure, additional average costs calculated for the provinces together can add up to ~ $50 billion (TDD), $6 billion (T or TN) and $7 billion (TX).
- Percentile values of 10th and 90th were evaluated for RCPs 4.5 and 8.5 scenarios. They are available for consultation in the supplementary material spreadsheets and graphs. The percentiles confirm the trend in the mean datasets; however, RCP4.5 percentiles show much more variation in values than RCP8.5, especially for precipitation variables (Schwalm et al. 2020).
- For a full description of cost values per province and per sector, please consult the supplementary cost calculation excel spreadsheets.

INCREMENT ANALYSIS (FUTURE CLIMATE SCENARIOS – BASELINE)

The last analysis on these results shows the difference between the baseline and future costs. These results were achieved by subtracting the future period (end of the century 2081–2100) by the baseline (1850–1900) and dividing the resulting value by the baseline. Alberta and Manitoba have the largest percentage increase in costs related to precipitation. Costs for infrastructures associated to mean precipitation are higher for the CMIP6 ensemble with increases of 100–200 per cent, especially in the sectors of marine engineering infrastructure. Rx1-day costs are more important for RCP8.5 with increases of 60–70 per cent on the other machinery sector. Rx5-day costs increase by 100–200 per cent for marine and transportation engineering infrastructure.

Costs related to temperatures' percentage increase is the highest since these affect several aspects of infrastructures in the CNC area. BC will see the highest impact on infrastructure costs due to changes in mean temperature; maximum and minimum temperatures percentage increase varies between 300–1,000 per cent and above. The most affected sectors are institutional buildings and oil and gas engineering construction. TDD variable has the highest percentage increase in costs for the last two sectors (above 1,000 per cent).

CC BIAS AND RESEARCH GAPS

To reduce bias in our analysis, we develop our cost calculations including CMIP6 and CMIP5 ensembles for different scenarios and percentiles. The new dataset from CMIP6 has a major difference in the degree of change of all variables compared to the CMIP5 ensemble. Due to the fast rate of change with which CC is occurring in these regions, it is more likely that the range of costs will fall within the most extreme and least conservative scenario SSP5-8.5 or RCP8.5. Despite our effort to provide a high-level CC cost estimation for several climate variables, extreme climate indices, specific hazards and infrastructure sectors, much work needs to be done to provide a clearer picture of these costs.

For instance, several hazards are influenced by cascading effects forced by the interconnection of climate variables and climate phenomena which can lead to domino events. A good example of these domino events is the recent wildfires and extreme rainfall in BC which occurred just months apart, causing landslides, flooding and much loss of life. A full understanding of the accumulation of domino events needs to be better assessed by the scientific literature. Future CC cost studies need to incorporate models that can identify where the accumulation of different phenomena may create hazardous weather for different sections of the CNC to prevent, adapt and build criteria designs for infrastructure that will include these risks.

Delay costs are created by the interconnection or accumulation of chokepoints in CNC; this will need to be assessed for future strategic planning and adaptation. Delay costs unaddressed in our analysis are a major part of the real estimation of costs that governments or companies often do not internalize. For example, maritime hazards and sea level rise can affect maritime infrastructures, port storage capacity and the import/export trade activities augmenting delay costs for the port, ships and exporters. The Port of Churchill is a good example of a region which will have to endure the accumulation of chokepoints. The Port of Churchill foresees an advantage in an increased navigable period due to a recurrent smaller sea ice season, but concomitantly faces limitations in the flow of goods coming from inland relying on a poor railway and road infrastructure in Manitoba. These connecting inland regions are prone to washouts and wildfires with increased vulnerability due to CC. Not adapting this infrastructure to domino effects will affect the capacity to deliver goods and merchandise safely and on time to the port.

6. DISCUSSION AND CONCLUSION

Our results included: a) climate variables (both baseline and future projections) across the buffer zones of the CNC areas; b) investment costs on nine types of infrastructure; and c) the percentage of useful life of these infrastructures in three provinces and one territory (AB, BC, MB and NT). CC infrastructure costs will increase in all selected variables and sectors with differences among regions and infrastructure types. Looking at our current baseline, the integrated analysis of the chokepoints showed that the leading areas of accumulated climate chokepoints concern Saskatchewan (0.47), Alberta (0.46), Manitoba (0.45) and the Northwest Territories (0.43). We did not calculate costs for Saskatchewan because the CNC areas in this province lacked significant population numbers and infrastructure data. For this reason, we excluded this province from our CC infrastructure cost analysis and included the next four provinces with the higher mean values for accumulated chokepoints.

The infrastructure investment CC cost results for the chokepoints including a discount rate of three per cent showed that when these climate costs are internalized, they reveal an increase in infrastructure investment values by more than 102 per cent, with total costs for the four provinces and the nine infrastructure sectors reaching more than $50 billion. When we consider the sum of all costs considering the projected climate variables individually, at the end of the century they could reach $65 billion, according to the CMIP6 SSP5-8.5 scenario, or $51 billion, according to the CMIP5 RCP8.5 scenario. If translated to a percentage perspective, values would peak to an almost +2,000 per cent increase (+1,993 per cent). The highest increases concern TDD (+1,000 per cent), changes in mean, minimum and maximum temperatures (+300–1,000 per cent), mean precipitation (+200 per cent) and in Rx5-day (+200 per cent). These projections have significant consequences for the development of infrastructure along the northern corridor, necessitating greater initial investment in climate-proofing infrastructure developments against multiple climatic hazards, ensuring maintenance and operational budgets reflect the costs of managing these changing risks and underpinning the importance of careful route selection.

The sectors mostly impacted in order include transportation engineering, electric power infrastructure, institutional buildings and oil and gas engineering. The provinces most impacted in order are Alberta, British Columbia and Manitoba. Building infrastructure will be particularly at risk in the Northwest Territories where the increase of thawing degree days and mean temperatures is projected to be the greatest. Wildfires in the CNC areas are also of particular concern, mostly in Alberta, the Northwest Territories and Manitoba. Sections of the CNC in the Northwest Territories and Manitoba are especially vulnerable to wildfire risk due to a projected increase in the drought regime, according to SPI and SPEI drought indices projections.

These final CC cost values should be considered carefully since they are a high-level analysis of the climate chokepoints in the CNC. This study has several limitations, including uncertainty in the climate projections, lack of available information on replacement costs of infrastructure at a municipality or district level, the vastness of the area analyzed, the lack of infrastructure currently built in these areas (for value comparison) and information or cost values on the delay, or how local populations would face transportation delays due to chokepoints in remote locations. Other extra costs that could not be computed include lack of available information on delay costs related to rescue and repair of equipment and costs associated with assistance crews having to travel long distances to provide support in the CNC regions. Furthermore, we had difficulties finding specific values in the life cycle of infrastructure types related to the energy sector, including transmission lines (poles).

Future studies should include all delay costs possible that are associated with assistance/rescue, death, inability to work/absenteeism, loss of productivity, loss of hours/days at work, health/medical costs and rehabilitation-physiotherapy in case of accidents. These costs would substantially increase the total CC costs considered in this study. Also, more localized analysis for specific municipalities that may play a role as transportation or infrastructure hubs in the CNC could serve as a basis to extrapolate costs to some of the uninhabited areas of the CNC, or how costs could look if such infrastructure were available in these areas.

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