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CLIMATE CHANGE AND IMPLICATIONS FOR THE PROPOSED CANADIAN NORTHERN CORRIDOR

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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, examining the potential for economic corridors in 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 providing information and analysis necessary to establish the feasibility and desirability of a network of multi-modal rights-of-way across middle and northern 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 help all Canadians benefit from improved infrastructure development in Canada.

This paper "Climate Change and the Implications for the Proposed Canadian Northern Corridor" falls under the Environmental Impacts theme of the program's eight research themes:

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Dr. Jennifer Winter
Program Director, Canadian Northern Corridor Research Program

CLIMATE CHANGE AND IMPLICATIONS FOR THE PROPOSED CANADIAN NORTHERN CORRIDOR*

Tristan Pearce, James D. Ford and David Fawcett

KEY MESSAGES

The key findings and recommendations of this review are:

Climate change is already impacting Northern Canada and infrastructure in the region. This includes infrastructure that is similar to what would exist in the proposed Canadian Northern Corridor, or other infrastructure that is a part of industries that drive the demand for expanded transportation through a corridor.

Based on future climate change projections, current impacts are expected to continue and intensify in the future. This means that existing and new infrastructure in Northern Canada will be at greater risk of damage.

Climate change impacts are likely to affect the construction of transportation infrastructure in the corridor. Future climate change projections must be integrated into regulations, codes and standards, design and route planning.

Maintenance of infrastructure in the corridor would need to be more robust to mitigate expected climate change impacts. This will likely increase the costs of maintenance, and maintenance procedures will need to be responsive to dynamic conditions over time.

Climate change could adversely impact and even halt the continuous operation of the corridor. Climate change could accelerate the deterioration of, and in some instances severely damage, corridor infrastructure. How changing climate conditions could affect "chokepoints" within the corridor system will be an important consideration.

The corridor will need to be responsive to the political economy of climate change. This includes the global movement to reduce greenhouse gas emissions and implications for the global economy that the movement of resources through the corridor depends on.

Local communities and Indigenous Peoples must be meaningfully consulted early and often. Early and ongoing communication is necessary to identify if a corridor is desirable and relevant and how it might be impacted by climate change.

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RÉPERCUSSIONS DU CHANGEMENT CLIMATIQUE SUR LE PROJET DE CORRIDOR NORDIQUE CANADIEN*

Tristan Pearce, James D. Ford et David Fawcett

MESSAGES CLÉS

Voici les principales conclusions et recommandations tirées de cet examen :

L'impact des changements climatiques se fait déjà sentir dans le Nord canadien et sur les infrastructures de la région. Cela concerne notamment des infrastructures semblables à celles proposées pour le corridor nordique canadien ou toute autre infrastructure utile aux industries qui poussent la demande de transport le long d'un corridor.

Sur la base des projections du changement climatique, l'impact actuel devrait s'intensifier à l'avenir. Cela veut dire que l'infrastructure en place ou prévue dans le Nord canadien sera davantage exposée aux dommages.

L'impact du changement climatique affectera probablement la construction de l'infrastructure de transport dans le corridor. La réglementation, les codes et normes de pratique, la conception et le tracé du corridor doivent tous tenir compte des projections du changement climatique.

L'entretien des infrastructures dans le corridor devrait être plus rigoureux afin d'atténuer les effets attendus du changement climatique. Cela augmentera probablement les coûts de maintenance, dont les procédures devront être adaptées à des conditions dynamiques au fil du temps.

Le changement climatique pourrait avoir un impact négatif et même interrompre l'exploitation continue du corridor. Le changement climatique pourrait accélérer la détérioration et, dans certains cas, endommager gravement l'infrastructure du corridor. Il est important de comprendre les effets du changement climatique sur les « goulots d'étranglement » dans le corridor.

Le concept du corridor doit tenir compte de l'économie politique du changement climatique. Cela comprend le mouvement mondial en faveur d'une réduction des émissions de gaz à effet de serre ainsi que ses répercussions sur l'économie mondiale qui influence le mouvement des ressources dans le corridor.

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* Cette recherche a été soutenue financièrement en partie par le gouvernement du Canada via Diversification de l'économie de l'Ouest Canada.

Les communautés locales et les peuples autochtones doivent être dûment consultés, et ce, dès le début et souvent au cours du développement du projet. Une communication précoce et continue est nécessaire pour déterminer si un corridor est souhaitable et pertinent et pour savoir de quelle façon il serait affecté par le changement climatique.

SUMMARY

The Canadian Northern Corridor (CNC) has been proposed as a potential solution to the challenges presented by limited transportation infrastructure in Northern Canada (Sulzenko and Fellows 2016). Building, operating and maintaining infrastructure in a northern corridor would be inherently challenging due to issues of remoteness and climate change. This paper reviews scientific evidence about the documented and potential impacts of climate change in Northern Canada and examines what the implications are for future CNC development.

Between 1948 and 2016, the annual average temperature across Northern Canada increased approximately 2.3 C, including a 4.3 C increase during winter months (Vincent et al. 2018). There is "virtual certainty" that this trend will continue, with the magnitude of increase dependent on future atmospheric greenhouse gas emissions (Zhang et al. 2019). Over a similar period, Canada experienced a 20-percent increase in precipitation, with Northern Canada experiencing the largest proportional increase (Vincent et al. 2018). Precipitation increases are expected to continue and be more concentrated at northern latitudes. This is expected to result in more snowfall in northern regions, turning into more rainfall and extreme precipitation throughout the century (Zhang et al. 2019).

As temperature and precipitation patterns have changed, the cryosphere has been impacted. Sea-ice extent and thickness have decreased in Northern Canada (Derksen et al. 2018). Under all emissions scenarios, reductions to sea-ice cover is expected to continue (Mudryk et al. 2018). Snow cover and accumulation, particularly in the fall and spring, have decreased across Canada, particularly in Northern Canada, and this trend is "virtually certain" to continue (Derksen et al. 2018). Permafrost temperatures have increased as well, resulting in permafrost thaw in some areas (Romanovsky et al. 2017). Under all emissions scenarios, air temperatures over permafrost areas are expected to increase, which is expected to result in the continued warming of permafrost across Northern Canada and the thawing of large areas by mid-century (Derksen et al. 2018). Glaciers and ice caps are losing mass at an accelerating rate, which is expected to continue and, along with reduced snow accumulation, begin to impact streamflow and water resources in some northern areas (Clarke et al. 2015).

Changes to meltwater and precipitation have shifted streamflow towards earlier peaks and higher flows in the winter and spring (Bonsal et al. 2019). Streamflow is projected to continue towards earlier onset of freshet and peaks in the winter and spring (Burn and Whitfield 2016; Burn et al. 2016). River and lake-ice-cover duration has also declined, a trend that is expected to continue (Cooley and Pavelsky 2016).

Coastal areas in Northern Canada are particularly vulnerable to climate change. Wave height and energy have increased, and the loss of sea-ice has exposed coastal areas and infrastructure to wave impacts (Greenan et al. 2018). This has increased erosion in some locations, especially those that have experienced permafrost thaw. These changes and impacts are compounded by warmer ocean

water temperatures that promote further permafrost thaw and thermal erosion (Derksen et al. 2018). Projected relative sea-level change at coastal locations and the progression of these conditions are expected to adversely affect coastal areas and infrastructure in the future (Greenan et al. 2018).

Climate change is also impacting the occurrence of extreme events and ecosystems. Changing climate conditions can increase the probability or intensity of extreme events, such as forest fires or floods (Zhang et al. 2019). Across Canada, shifts in the distribution of species and range expansion and contraction have also been documented and attributed to climate change (Nantel et al. 2014).

These documented and projected future climate change impacts threaten the construction, maintenance and operation of infrastructure within the corridor. Climate change impacts are likely to affect the feasibility and costs of some infrastructure and create ongoing challenges to operations. Climate change impacts are highly localized, and a disturbance at one chokepoint in the corridor could compromise the operation of the whole corridor. More research is needed to examine climate change impacts at local scales to understand the characteristics of the physical environment and how it is changing, as well as how existing human activities overlap with the proposed corridor. Efforts are needed to engage relevant local communities and Indigenous Peoples early in corridor discussions to identify if a corridor is desirable and relevant to them and, if so, whether it can be developed in a manner that sustains livelihoods, culture, health and well-being.

Canada's commitment to reducing greenhouse gas emissions (e.g., the Paris agreement), the responses of the global economy to climate change, and the existence (or lack thereof) of a social licence for the development of infrastructure that contributes to greenhouse gas emissions all need to be considered in the visioning of the corridor. Will a Canadian Northern Corridor be relevant in an economy that is moving away from fossil fuel dependency and towards renewable energy? If so, will building, operating and maintaining the infrastructure within a corridor be feasible under changing climatic conditions, such as those outlined in this report?

RÉSUMÉ

Le corridor nordique canadien (CNC) est proposé comme solution potentielle aux défis posés par le manque d'infrastructure de transport dans le Nord canadien (Sulzenko et Fellows 2016). La construction, l'exploitation et l'entretien de l'infrastructure du corridor nordique sont intrinsèquement difficiles en raison des problèmes de l'éloignement et du changement climatique. Cet article passe en revue les données scientifiques sur l'impact documenté et potentiel du changement climatique dans le Nord canadien et en examine les répercussions pour le développement éventuel du CNC.

Entre 1948 et 2016, la température moyenne annuelle dans le Nord canadien a augmenté d'environ 2,3 °C, notamment une augmentation de 4,3 °C pendant les mois d'hiver (Vincent et al. 2018). Il existe une « quasi certitude » que cette tendance se poursuivra; l'ampleur de l'augmentation dépendra des futures émissions de gaz à effet de serre dans l'atmosphère (Zhang et al. 2019). Au cours de la même période, environ, le Canada a connu une augmentation de 20 % des précipitations. L'augmentation la plus forte, toute proportion gardée, est enregistrée dans le Nord canadien (Vincent et al. 2018). On prévoit que l'augmentation des précipitations s'intensifie dans les latitudes nordiques. Cela devrait entraîner davantage de chutes de neige, lesquelles se transformeront de plus en plus en pluie ou en précipitations extrêmes au cours du siècle (Zhang et al. 2019).

La cryosphère est touchée par le changement des modèles de température et de précipitations. L'étendue et l'épaisseur de la glace de mer ont diminué dans le Nord canadien (Derksen et al. 2018). Tous les scénarios d'émissions prévoient une réduction continue de la couverture de glace de mer (Mudryk et al. 2018). La couverture et l'accumulation de neige, en particulier à l'automne et au printemps, ont diminué partout au Canada, en particulier dans le Nord, et il est « quasi certain » que cette tendance se poursuivra (Derksen et al. 2018). La température du pergélisol a aussi augmentée, ce qui entraîne un dégel dans certaines régions (Romanovsky et al. 2017). Tous les scénarios d'émissions prévoient une augmentation de la température de l'air au-dessus des zones de pergélisol, ce qui devrait entraîner un réchauffement continu du pergélisol dans le Nord canadien ainsi que le dégel de vastes zones d'ici le milieu du siècle (Derksen et al. 2018). Les glaciers et les calottes glaciaires perdent de la masse à un rythme accéléré; tendance qui devrait se poursuivre et, avec la réduction de l'accumulation de neige, aura un impact sur le débit et les ressources en eau dans certaines régions nordiques (Clarke et al. 2015).

Les changements en matière de précipitations et d'eau de fonte influencent l'écoulement fluvial, qui connaît des débits de pointe précoces et plus élevés en hiver et au printemps (Bonsal et al. 2019). On prévoit des débuts de crue printanière plus précoces ainsi que des débits de pointe en hiver et au printemps (Burn et Whitfield 2016; Burn et al. 2016). La période de couverture de glace sur les rivières et les lacs a également diminué, une tendance qui devrait aussi se poursuivre (Cooley et Pavelsky 2016).

Les zones côtières du Nord canadien sont particulièrement vulnérables aux changements climatiques. La hauteur et l'énergie des vagues ont augmenté, et la perte de glace de mer expose l'infrastructure et les zones côtières à l'impact des vagues (Greenan et al. 2018). Cela accroît l'érosion à certains endroits, en particulier là où il y a dégel du pergélisol. Les températures océaniques plus chaudes viennent aggraver la situation en favorisant le dégel du pergélisol et l'érosion thermique (Derksen et al. 2018). L'élévation projetée du niveau de la mer dans les zones côtières ainsi que l'aggravement des conditions devraient avoir des effets négatifs sur les côtes et sur l'infrastructure (Greenan et al. 2018).

Le changement climatique a également un impact sur la survenue d'événements et d'écosystèmes extrêmes. Les conditions climatiques peuvent accroître la probabilité ou l'intensité d'événements extrêmes, tels que les incendies de forêt ou les inondations (Zhang et al. 2019). Partout au Canada, des changements dans la répartition des espèces ainsi que l'expansion ou la contraction des aires de répartition sont bien documentés et attribués aux changements climatiques (Nantel et al. 2014).

L'impact du changement climatique documenté ou projeté met à risque la construction, l'entretien et l'exploitation des infrastructures du corridor. Le changement climatique affectera possiblement la faisabilité et le coût de certaines infrastructures, en plus de poser des défis constants pour leur exploitation. Les impacts du changement climatique sont très localisés, et la perturbation d'un seul goulot d'étranglement peut compromettre l'exploitation de l'ensemble du corridor. Des recherches supplémentaires sont nécessaires pour examiner l'impact du changement climatique à l'échelle locale afin de mieux comprendre les caractéristiques de l'environnement physique et son évolution, ainsi que la façon dont les activités humaines actuellement en place se chevauchent au corridor proposé. Des efforts seront nécessaires dès le début pour favoriser la participation des communautés locales et des peuples autochtones aux discussions, et ce, afin de déterminer si un corridor est souhaitable et pertinent pour eux et, le cas échéant, s'il peut être développé de manière à soutenir les moyens de subsistance, la culture, la santé et le bien-être.

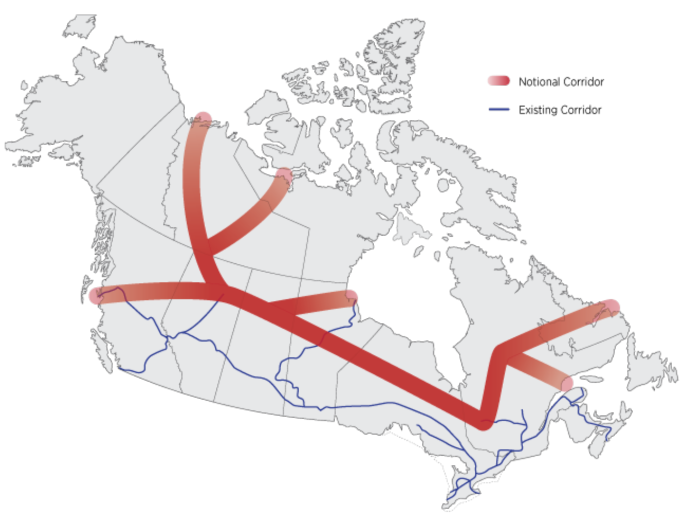
L'engagement du Canada à réduire les émissions de gaz à effet de serre (p. ex., l'Accord de Paris), la réaction de l'économie mondiale face aux changements climatiques et l'existence (ou l'absence) d'acceptabilité sociale quant au développement d'infrastructures qui contribuent aux émissions de gaz à effet de serre doivent tous être pris en compte dans la vision du corridor. Un corridor nordique canadien est-il pertinent dans une économie qui s'éloigne de la dépendance aux combustibles fossiles et qui se tourne vers les énergies renouvelables? Dans l'affirmative, la construction, l'exploitation et l'entretien de l'infrastructure du corridor seront-ils réalisables dans le contexte du changement climatique tel que décrit dans ce rapport?

1. INTRODUCTION

Transportation infrastructure is limited in most of Canada's northern regions, challenged by remoteness, geography, environmental conditions and under-investment. This has implications for the competitiveness, growth, diversification and prosperity of these regions (Pendakur 2017). Furthermore, existing infrastructure in the south is experiencing east-west bottlenecks that are restricting access to international markets through export shipping (Transport Canada 2017; Fellows and Tombe 2018). One response that has been proposed to these challenges is the development of a Canadian Northern Corridor (CNC) (Sulzenko and Fellows 2016). The CNC proposal would involve the development of a multimodal right-of-way (ROW) stretching across Northern Canada.

As proposed by the University of Calgary School of Public Policy (SPP) (Sulzenko and Fellows 2016), the CNC would be between one and 10 kilometres in width and approximately 7,000 kilometres in length (Figure 1). This ROW 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 and could improve development and reduce the cost of living in remote northern areas (Sulzenko and Fellows 2016). The development of the corridor would be a joint effort between public and private sectors and would make the construction and operation of critical infrastructure for both more efficient, and open-up possibilities for private investment in Northern Canada (Sulzenko and Fellows 2016).

Figure 1: A possible route of the Canadian Northern Corridor proposed by the University of Calgary School of Public Policy (Sulzenko and Fellows 2016).



The development of the corridor concept will, of course, be a significant undertaking and require extensive research and effort in multiple areas, such as defining governance and funding structures, ensuring appropriate consultation with local communities and Indigenous Peoples, and understanding infrastructural and environmental opportunities and risks. The potential impacts of climate change will also be an area of importance. Building, operating and maintaining infrastructure in Northern Canada is already inherently challenging, due to issues of 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). Current climate change impacts have been recorded at rates greater than what climate models projected and are expected to continue, and in some instances worsen, in the future (ECCC 2016; Bush and Lemmen 2019). As such, past climate can no longer be considered a reliable guide in planning future infrastructure (Suter, Streletskiy and Shiklomanov 2019). The construction, operation and maintenance of infrastructure within a northern corridor would have to be undertaken with a clear understanding of expected future climate impacts.

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 establishment, governance and regulatory oversight of the corridor. This paper specifically reviews scientific evidence about the potential impacts[1] of climate change in Northern Canada and examines the implications for future corridor development. Our review is based on an analysis of existing knowledge, drawing upon international and national climate change assessments, including Canada's Changing Climate Report, released by Natural Resources Canada (Bush and Lemmen 2019), and other peer-reviewed and grey literature.

This paper begins by presenting the results of the review of potential impacts of climate change in Northern Canada. Documented and projected future climate change impacts are described for a selection of relevant environmental attributes. The implications of these impacts for future corridor development are then discussed and knowledge gaps and future research needs are identified.

The paper draws upon studies that use climate models and greenhouse gas (GHG)[2] emissions scenarios to identify potential future climate change impacts. Projections are developed using computer earth-system models to simulate how the climate will respond to different levels of climate-forcing inputs (e.g., GHG) and how these changes could interact with other physical and biogeochemical processes. Because future GHG emissions are unknown, climate models use different low-, medium- and high-emissions scenarios based on socio-economic and policy modelling,

1 "Impacts" include the effects of climate change on natural and human systems (e.g., livelihoods, ecosystem, culture, infrastructure, etc.) (IPCC 2014). In this report, "impacts" primarily refers to the interaction of climate change and related events with the biophysical environment and the outcomes or consequences of those.

2 Greenhouse gases (GHGs) are gases found in the atmosphere, both naturally and due to human activity, such as carbon dioxide, methane, nitrous oxide and water vapour. These gases absorb and emit heat radiated from the Earth and other parts of the atmosphere. For the purpose of this paper, GHG emissions are primarily referring to GHGs emitted from human activities, which have been the main driver of climate warming during the industrial era (IPCC 2014; Lemmen and Bush 2019).

known as the Representative Concentration Pathways (RCPs). Studies often use different RCPs in constructing projections to manage uncertainty, but some degree of uncertainty is inevitable. The projections of current climate models are consistent across the next 10 to 30 years, but then start to diverge, reflecting uncertainty based on future GHG emissions and the complexity of the affected systems at smaller scales. Because of this, when climate models are used to understand future climate change at the regional level, variability and uncertainty grow. There are two methods to downscale model projections — statistical downscaling and dynamic downscaling — both of which have benefits and weaknesses and have been applied in Canada at large resolutions (e.g., 15-50 kilometre pixels). The future climate change impacts discussed in this paper are primarily derived from climate projections for low-, medium- and high-emissions scenarios synthesized by Natural Resources Canada (Flato et al. 2019). In some cases, we reference specific models that were included in the overall climate projections. We have drawn projections most heavily from high-GHG-emissions scenarios because they are represented as "business as usual" within much of the literature (e.g., Cohen et al. 2019), but it is worth noting that high-emissions scenarios may be more accurately read as the "worst-case scenario" (Hausfather and Peters 2020).

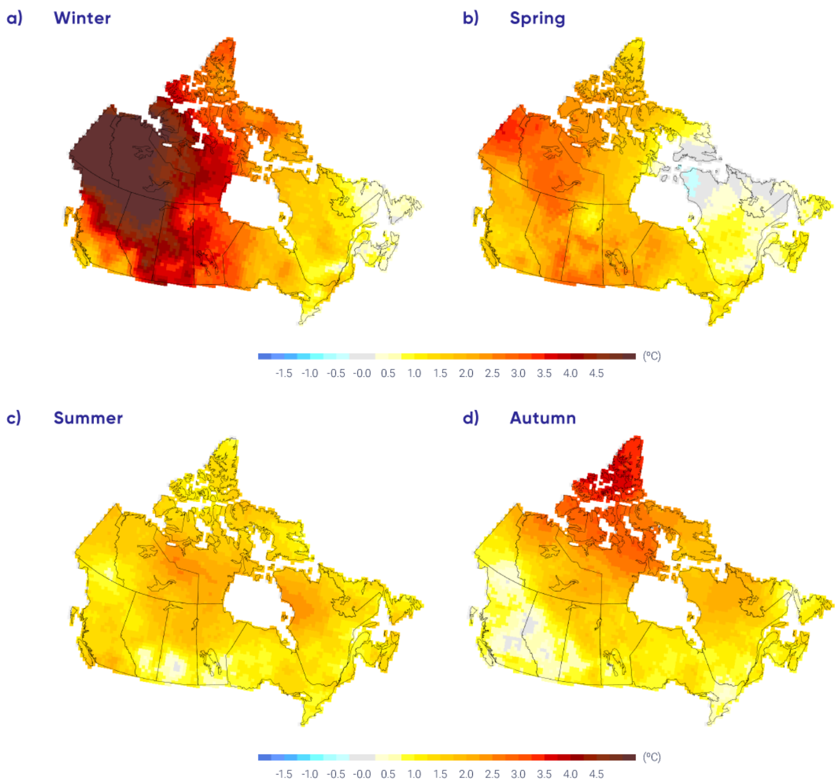
Finally, for consistency throughout the paper we have used the term "Northern Canada" in lieu of "Canadian North," "northern regions of Canada" and "proposed corridor route." Northern Canada is often defined as the region north of 60 degrees latitude. However, because of the geographic scope of the proposed corridor and its prominence in Northern Canada — including marine areas that represent potential ports and shipping lanes — as well as for clarity, we have used "Northern Canada" as a catch-all term for areas including and north of the proposed corridor route (Figure 1).

2. CLIMATE CHANGE IMPACTS IN NORTHERN CANADA

2.1. TEMPERATURE

Between 1948 and 2016, the annual average temperature across Canada increased approximately 1.7 C and it is a "virtual certainty" that this trend will continue based on current atmospheric GHG and emissions levels (Zhang et al. 2019). Changes in temperature have been more heavily concentrated in the winter and in Northern Canada, the Prairies and northern British Columbia (Cohen et al. 2019; Wan, Zhang and Zwiers 2019). For example, between 1948 and 2016, Northern Canada experienced an annual average temperature increase of 2.3 C, including a 4.3 C increase in the winter and 1.6 C increase in the summer, compared to 1.7 C, 3.3 C and 1.5 C increases across Canada as a whole (Figure 2) (Vincent et al. 2015, Vincent et al. 2018). This has been accompanied by an increase in the lowest daily minimum temperatures, days with "very warm temperatures" and freeze-thaw cycles, and has reduced frost days, consecutive frost days and ice days (Vincent et al. 2018).

Figure 2: The observed change in seasonal mean temperature across Canada for the period of 1948–2016 (from Bush and Lemmen 2019, updated from Figure 3 of Vincent et al. 2015).



Further temperature increases are projected across Canada under all GHG-emissions scenarios, displaying variability depending on the scenario. Projections in Northern Canada show the largest increase in annual average temperature: 1.8 C for a low-emissions scenario and 2.7 C for a high-emissions scenario by 2031–2050; and 2.1 C and 7.8 C for low- and high-emissions scenarios by 2081–2100 (based on 1986–2005 mean values) (Cohen et al. 2019). These changes are expected to be concentrated in the winter and to result in longer growing seasons, fewer heating degree days and more cooling degree days,[3] as well as more extreme high temperatures and fewer low extremes (Jeong et al. 2016; Vincent et al. 2018).

2.2. PRECIPITATION

From 1948 to 2012, changes to precipitation in Canada were less spatially consistent than changes to temperature, but Canada did experience an increase in precipitation of approximately 20 per cent (Vincent et al. 2018). The annual average

3 Heating degree days are the annual sum of days with a temperature below 18 C and cooling degree days are the annual sum of days with a temperature above 18 C (Zhang et al. 2019). These measures are important in energy planning, as they quantify energy demand (or potential energy demand) based on the need for heating or air conditioning, respectively. For example, as heating degree days decrease and cooling degree days increase, energy demand will increasingly shift from heating to air conditioning.

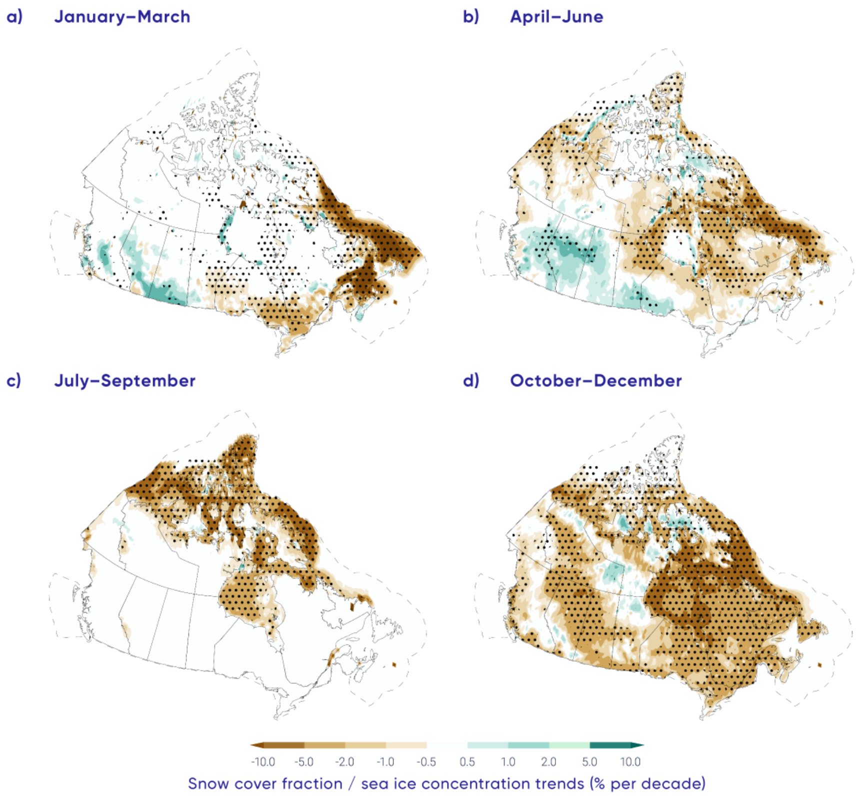
number of days with rainfall (at least one millimetre) experienced a statistically significant increase, while the annual average number of days with snowfall (at least one millimetre) was more regionally varied, with the western provinces and Atlantic region experiencing decreases in most locations, and eastern and Northern Canada experiencing relative increases in most locations (Mekis et al. 2015; Vincent et al. 2018). Southern Canada experienced larger actual increases in precipitation, but Northern Canada experienced the largest proportional increase in precipitation relative to normal levels, including more snowfall (for example, an additional 7.3 days per year with snowfall and an additional 2.3 days per year with heavy snowfall) (Vincent et al. 2018). A change in the form and frequency of precipitation (e.g., snow to rain) was experienced in many areas (Vincent et al. 2015). Across Canada, there was a lack of statistically significant change in the number of extreme precipitation events (for instance, the highest-precipitation day, annually) (Mekis et al. 2015).

Precipitation changes in the future are expected to be proportionally more concentrated to the higher latitudes in Canada, and the greatest changes will be experienced in the winter (Flato et al. 2019). Limited changes to precipitation patterns in Northern Canada (e.g., a 10-per-cent increase) are projected between 2031–2050; however, under high-emissions scenarios, the changes will be much larger by 2081–2100 and could increase by as much as 30 per cent in the Canadian Arctic (Zhang et al. 2019). Precipitation increases across Northern Canada are expected to begin as an increase in snowfall, eventually leading to more rain and rain-on-snow events as temperatures increase over time (Jeong and Sushama 2017). Extreme precipitation events are also expected to increase in frequency and magnitude (Zhang et al. 2019).

2.3. SEA ICE

Sea-ice extent in Arctic and Atlantic Canada and multi-year ice in the Arctic have both decreased at an accelerating rate since 2008 (Figure 3) (Derksen et al. 2018; Cohen et al. 2019). Multi-year sea ice (MYI) — ice that has survived at least one melt season — is becoming more mobile (Howell and Brady 2019) and is being replaced by seasonal first-year ice (FYI), the new ice growth of a single season (Comiso 2012; Babb et al. 2019). These changes can be problematic for two reasons: 1) FYI drifts more and melts quicker than MYI (Tandon et al. 2018), which could lead to a quicker loss of sea-ice extent (Derksen et al. 2018) and presents more hazards to communities that rely on sea-ice for travel and livelihoods (Ford et al. 2019); and 2) MYI has started to drift from the central Arctic Ocean into the Canadian Arctic Archipelago (CAA) and from the CAA to the Maritimes, creating significant shipping hazards (Barber et al. 2018; Howell and Brady 2019). Sea-ice thickness in the Arctic has also been observed to be decreasing, along with more ice-free open water in the summer (Parkinson 2014). These changes are extending the shipping season in the Arctic Ocean and opening up new routes, and ship traffic has nearly tripled in the Canadian Arctic over the last decade, bringing both opportunities and challenges to communities (Dawson et al. 2020). At the same time, sea-ice is important for a whole web of unmaintained seasonal trails that are used by communities to access culturally important locations for hunting, fishing, heritage sites and other communities. Evidence from numerous regions in Northern Canada indicates that the period at which such trails are able to be used is decreasing, along with the safety of using such trails (Durkalec et al. 2015; Clark et al. 2016; Ford et al. 2019).

Figure 3: The trends in sea-ice concentration and terrestrial snow cover for the period of 1985–2015 (from Bush and Lemmen 2019, reproduced from Mudryk et al. 2018).



Arctic sea-ice extent has an inverse correlation with global temperatures and GHG emissions (Notz and Stroeve 2016). As a result, sea-ice extent across the Arctic is projected to decline under all emissions scenarios (IPCC 2019). Climate projections using low-, medium- and high-emissions scenarios all project significant reductions in sea-ice extent in the Canadian Arctic: under high-emission scenarios, there is a projected 50-per-cent probability that extensive areas could be ice-free (five-per-cent ice cover or less) at the end of summer 2050 (Mudryk et al. 2018). Hudson Bay has a high probability of being ice-free for four consecutive months by mid-century, a two-month increase over the present day (Mudryk et al. 2018). Climate projections for Atlantic Canada for 2040–2070 indicate that ice-formation and ice-out dates in the St. Lawrence estuary and gulf will be 10 to 20 days later and 20 to 30 days earlier, respectively (Senneville et al. 2014). Under high-emissions scenario projections, the Atlantic coast will also be ice-free during the winter by mid-century (Loder, van der Baaren and Yashayaev 2015). This would lead to longer open-water periods in many regions and more drifting ice in areas such as the Northwest Passage and Atlantic Canada (Haas and Howell 2015; Loder et al. 2015). Herein, the Arctic Ocean is rapidly transforming into a navigable ocean, significantly reducing sailing distance between Europe and Asia, yet modelling studies suggest that a combination of legal, infrastructural, technological, climatic and economic challenges, and cheaper alternative options (e.g., transit via the Suez Canal or Trans-Siberian Railway), are likely to constrain the development of circumpolar shipping routes (Li, Ringsberg and Rita 2020; Zeng et al. 2020).

2.4. SNOW COVER

Snow cover and the accumulation of snow have decreased across most areas of Canada (Figure 3) (Derksen et al. 2018). Increasing temperatures in the shoulder seasons — fall and spring — result in less build up, earlier melt and more snow falling as rain (Bonsal et al. 2019). This has led to a shift towards later onset of snow cover, less duration of snow and earlier snowmelt in the spring, and less snowpack storage (Mudryk et al. 2015; Vincent et al. 2015; DeBeer et al. 2016). In Northern Canada, snow-cover extent has been significantly reduced during the spring months (April through June) and fall months (October through December) (Brown et al. 2017; Mudryk et al. 2018), and community members in many remote and Indigenous communities have observed less snowfall, wetter snow and overall less snow cover throughout the year (Ford et al. 2016).

Based on climate projections, the decrease in snow cover and accumulation across most areas of Canada are "virtually certain" to continue over the next century under all scenarios (Derksen et al. 2018). Between 2020 and 2050, the most significant loss of snow cover across Canada is expected to occur during the shoulder seasons (Thackeray et al. 2016) and climate models project an increase in precipitation falling as rain and rain-on-snow events (Jeong and Sushama 2017). In Northern Canada, a shortened snow-accumulation period due to rising temperatures is expected to offset an increase in snowfall in winter months (Derksen et al. 2018; Cohen et al. 2019).

2.5. PERMAFROST

Across Northern Canada, permafrost temperatures have increased, which has led to increases in the thickness of the active layer[4] during the summer seasons and the thawing of ground ice (Ednie and Smith 2015; Romanovsky et al. 2017; Smith et al. 2017). Specific changes are localized; over the last three to four decades, the central Mackenzie River valley has seen increases in permafrost temperatures of approximately 0.1 C per decade and the High Arctic has seen increases at a rate of approximately 0.3–0.5 C per decade (Romanovsky et al. 2017), while Nunavik has seen increases of approximately 0.5–0.9 C since 2000 (Allard, Sarrazin and

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

Hérault 2015). This has led to the formation of thermokarst[5] landforms across much of Northern Canada, including observations of lake formation and collapse, loss of permafrost mounds and increases in the size of permafrost ponds (Beck et al. 2015; Olefeldt et al. 2016; Jolivel and Allard 2017; Mamet et al. 2017). Similar changes to permafrost in Russia due to climate change have led to a decrease the bearing capacity[6] of permafrost (Streletskiy and Shiklomanov 2016).

Permafrost can be influenced by a number of other climate change impacts, such as more intense rainfall and changes to vegetation and snow accumulation (Kokelj et al. 2015), which makes projecting climate-related impacts to permafrost complicated (Derksen et al. 2018). Under all GHG-emissions scenarios, air temperatures over permafrost areas are expected to increase, which is expected to result in the continued warming of permafrost across Northern Canada and the thawing of large areas by mid-century (Derksen et al. 2018). Models using low- and medium-emissions scenarios have projected that the area underlain by deep permafrost in Canada will decrease approximately 16 to 20 per cent by 2090 relative to 1990, and some models even project permafrost thaw through the late-21st century under an emissions scenario that stabilizes temperature change by mid-century (Zhang, Chen and Riseborough 2008a; Zhang, Chen and Riseborough 2008b).

These changes are expected to have wide-ranging impacts on infrastructure. Permafrost regions in Russia, for example, are expected to lose approximately 50 per cent of their bearing capacity by 2059 under a high-emissions scenario (Streletskiy et al. 2019). Modelling work by Suter and others (2019), using a high-emissions scenario applied across the Arctic, identifies Northern Canada as a region projected to be particularly affected, with lifecycle replacement costs increasing by 33.6 per cent by mid-century due to climate impacts, putting 19 per cent of infrastructure at risk. In dollar terms, they estimate the increase cost to exceed $4 billion (Canadian dollars). In all the Arctic, the mean annual costs to address increased lifecycle replacement costs and direct damages due to climate change are highest in the Yukon and Northwest Territories, as a percentage of gross regional product (Suter et al. 2019).

2.6. GLACIERS AND ICE CAPS

There has been an accelerated mass loss of glaciers and ice caps across Canada due to the warming climate. For example, in the CAA, the loss of glacier and ice-cap mass has accelerated over the last 15 years (Derksen et al. 2018), increasing from 22 gigatonnes of mass loss per year between 1995 and 2000 (Abdalati et al. 2004) to approximately 67 gigatonnes per year between 2003 and 2010 (Jacob et al. 2012), and further acceleration up to 2015 (Harig and Simons 2016). Glaciers in the Columbia Icefield in the Rocky Mountains lost 22.5 per cent (an average of

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

6 The ability of permafrost to support a structural load (Streletskiy et al. 2019).

approximately 1.1 kilometre) of their total area between 1919 and 2009 (Tennant and Menounos 2013), and glaciers and icefields in the Yukon lost approximately 22 per cent of their area from 1957 to 2007 (Barrand and Sharp 2010).

The mass loss of glaciers and ice caps is projected to continue; based on climate models using a medium-emissions scenario, many glaciers in the Canadian Western Cordillera will lose 74 to 96 per cent of their volume by 2081 (Clarke et al. 2015) and glaciers in the CAA are projected to lose 18 per cent of their ice mass by 2100 (Radić et al. 2014). This will have an impact on the regional stream flows and water resources in Western Canada, particularly by the mid-to-late century (Clarke et al. 2015; Fyfe et al. 2017).

2.7. COASTAL IMPACTS

Coastal areas will be subject to numerous climate-related impacts, each of which will interact. This includes: sea-level change, permafrost thaw and 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 conditions.

2.7.1. Sea-level rise and extreme water levels

Local sea-level rise is relative to the level of vertical land motion,[7] such as local land uplift or subsidence. Different coastal areas in Canada have experienced different relative-sea-level[8] changes. For example, relative sea level has risen along the Beaufort Sea coastline more quickly than the global average due to land subsidence, while the eastern Arctic and Hudson Bay have actually experienced a decline in relative sea level (Cohen et al. 2019).

Global sea level is expected to continue to rise over the next century under all GHG-emissions scenarios (IPCC 2019) and the Canadian coastline will continue to experience localized impacts based on vertical land motion. Based on the median projection of models using a low-emissions scenario, Tuktoyaktuk is projected to see 41.4 centimetres in sea-level rise by 2100; Churchill is projected to experience -81.9 centimetres of relative sea level rise (81.9 centimetres of sea-level drop), given high rates of post-glacial land emergence; Prince Rupert is projected to experience 43.5 centimetres of rise; and Sept-Îles is expected to experience little relative change to current sea level (James et al. 2014). Regardless of the emissions scenario, sea level is projected to rise or drop significantly in three of the five potential CNC ports over the course of the 21st century (Table 1). This could impact the feasibility of shipping or the operation of shipping infrastructure at

7 The uplift (rise) or subsidence (drop) of the ground surface at a location due to processes such as glacial isostatic 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).

8 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).

these locations. At the ports that are projected to experience significant relative sea-level rise, sea-level rise will combine with other factors (see below) to increase the frequency of extreme-water-level events. Under a high-emissions scenario, a one-in-25 year event in Tuktoyaktuk could become one-in-four year event, and a 10-year event could increase from a 1.1-metre storm surge to 2.1-metre storm surge (Lamoureux et al. 2015). Even with adaptation efforts (such as coastal-protection measures), the IPCC estimates that low-lying Arctic communities, such as Tuktoyaktuk, will experience moderate to high risk relative to today, even in a low-emission pathway by mid-century (Oppenheimer et al. 2019).

Table 1: Projected relative sea-level change at 2100 (relative to 1986–2005) for five potential port communities based on the conceptual CNC route (data from James et al. 2014).

Potential port	Low emissions	Medium emissions	High emissions
Prince Rupert, B.C.	43.5 cm	46.4 cm	57.7 cm
Tuktoyaktuk, N.W.T.	41.4 cm	48.2 cm	67.9 cm
Churchill, Man.	-81.9 cm	-74.8 cm	-58.8 cm
Sept-Îles, Que.	-0.2 cm	10.0 cm	30.9 cm
Goose Bay, N.L.	-13.5 cm	-5.9 cm	10.9 cm

2.7.2. Waves

As sea-ice-extent decreases (see section 4.7.3), wave energy and wave height have the potential to increase due to greater fetch[9] (Thomson and Rogers 2014). Shoreline orientation, wind direction and shoreline bathymetry[10] will dictate the size and impacts of wave activity (Serafin et al. 2019). Wave height, energy increases and increased wave-season duration have already been observed in the Canadian Arctic, particularly in the Beaufort Sea region (Thomson et al. 2016; Greenan et al. 2018).

As sea-ice extent decreases, wave height, energy and seasons are projected to experience significant increases in the future along most northern coastal regions (Aksenov et al. 2017; Casas-Prat, Wang and Swart 2018). This is expected to have the largest impacts on the north-facing coasts in the Canadian Arctic due to the mean wave direction being southward (Greenan et al. 2018).

2.7.3. Storm surge

Sea-level rise, natural tides and stronger waves will combine to produce an increased chance of flooding and storm surges (Khon et al. 2014). In the Canadian Arctic there has been an observed positive correlation between open water, air

9 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).

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

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).

2.7.4. Erosion

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 averaged 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 in some locations during some periods (Figure 4) (Solomon 2005). Coastal-erosion processes are expected to increase under all emissions scenarios, particularly in areas of less sea ice and more relative sea-level rise (Greenan et al. 2018). The exception to these projections is areas that receive eroded material that is redistributed as a part of the coastal sediment balance (Overeem et al. 2011).

Figure 4: Coastal areas in the western Canadian Arctic are changing rapidly due to the impacts of climate change. The large pinnacles in this photo were eroded out to sea several days after this photo was taken (photo credit: Weronika Murray, published by the Government of Canada, 2019).

2.8. HYDROLOGY

Climate change will have numerous impacts on hydrological processes across Canada. The scientific literature focuses on the impacts of climate change on two key areas of hydrology: (1) water levels and streamflow; and (2) lake and river ice.

2.8.1. Water levels and streamflow

The impacts of climate change on water levels and streamflow exhibit a lot of variation based on location, streamflow regime[11] (e.g., rainfall-dependent or melt-dependent watersheds) and other factors (e.g., river-channel shape). Actual annual streamflow volume has shown variable or no significant trends in various basins across Canada (Nalley, Adamowski and Khalil 2012; Déry et al. 2016; Hernández-Henríquez, Sharma and Déry 2017; Rood et al. 2017). Streamflow, however, has shifted towards earlier peaks and higher flows in winter and spring and lower summer flows, and there has been an overall decrease in high-flow events and increase in low-flow events (Bonsal et al. 2019). Water levels are also impacted in a variable manner based on local conditions. In particular, some 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).

Streamflow is projected to continue towards: earlier onset of freshet[12] and peaks in the winter and spring; smaller snowmelt events; and a shift from nival (snowmelt) regimes to pluvial (rainfall), or mixed nival-pluvial regimes (Burn and Whitfield 2016; Burn, Whitfield and Sharif 2016). Similar to current trends in actual annual flow, future trends are expected to vary. 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).

2.8.2. River and lake ice

Across Canada, seasonal lake-ice-cover duration has declined since the 1960s, due to later freeze-up in the fall and earlier break-up in the spring (Derksen et al. 2018). Even Canada's northernmost lake, Ward Hunt Lake, which had previously remained perennially frozen, melted completely in 2011 and 2012 (Paquette et al. 2015). There is also evidence of the earlier breakup of river ice, relative to baseline breakup times in most locations (Prowse 2012).

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11 Streamflow in Canadian basins is typically defined as nival (dominated by snowmelt), glacial (dominated by glacial melt), pluvial (dominated by rainfall), or a mix of multiple (Bonsal et al. 2019).

12 Increased streamflow as a result of snow and ice melt in the spring (Derksen et al. 2018).

Reductions in ice-cover duration are expected to continue. Spring lake-ice breakup is projected to be 10 to 25 days earlier by 2050 (compared to 1961–1990) and freeze-up during the fall is projected to be five to 15 days later (Brown and Duguay 2011; Dibike et al. 2012). Increasing temperatures, combined with changes to ice strength and stream-flow peak periods, are also projected to influence earlier river-ice breakup in the spring in northern regions (Cooley and Pavelsky 2016). How changes to river ice will combine with flow changes to impact ice jams and floods is not completely understood (Beltaos and Prowse 2009). Frozen rivers and lakes are important for seasonal transportation in Northern Canada, including accessing remote mines, while warming and changing ice regimes compromise the operating period and safety of winter roads constructed on the frozen water. These temporary, maintained roads provide low-cost transport to communities, resource development sites and construction projects (Pearce et al. 2010; Hori et al. 2012; Hori et al. 2018). Northern Canada is expected to see a decrease of 14 per cent (approximately 400,000 square kilometres) in the amount of land area that is accessible by winter roads by mid-century, based on a 2000 to 2014 baseline and medium-emissions scenario (Stephenson, Smith and Agnew 2011).

2.9. EXTREME EVENTS

Climate change can influence the probability or intensity of extreme events such as forest fires or floods (Zhang et al. 2019). Changing temperature, precipitation and wind patterns have increased the likelihood and severity of droughts and wildfires, with the largest changes being experienced on the Prairies (Wang et al. 2015; Flannigan et al. 2016). This increased fire and drought risk contributed to the extreme wildfire conditions that produced the 2016 Fort McMurray wildfire (Kirchmeier-Young et al. 2017). The increasing magnitude and frequency of extreme wildfire and drought conditions is expected to continue (Wotton, Flannigan and Marshall 2017; Kharin et al. 2018).

Flooding events are also projected to increase across Canada, although in some locations floods may eventually become smaller. There is a lack of detectable change in extreme precipitation events that have led to flooding thus far, but projected increases in extreme precipitation events are expected to increase inland flooding potential, particularly in urban areas (Bonsal et al. 2019). Changing hydrological patterns due to temperature changes is projected to produce changes to flood patterns as well (e.g., shift to pluvial regimes) (Burn and Whitfield 2016), with implications for water and food security in vulnerable locations (Golden, Audet and Smith 2015; Sohns et al. 2019).

2.10. ECOSYSTEMS

The impacts of climate change on ecosystems are numerous and variable (Post et al. 2013; Post et al. 2019). 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[13] extent (Hutchings et al. 2012; Steiner et al. 2015; Greenan et al. 2018). These changes and disruptions have the potential to 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 instance, there is potential for the increased northern movement of several commercial fish species and associated fishing activity, although significant uncertainties remain in how fish will be affected by climate change, 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 (e.g., Wesche et al. 2010; Hlimi et al. 2012; Skinner et al. 2013; Kenny et al. 2018; Lam et al. 2019).

Based on climate projections, it is expected that species and ecosystem ranges will continue to shift, expand, contract or even fragment (Nantel et al. 2014). How different ecosystems and species respond will depend on specific species and how interconnected species respond, as well as the local geography. Some species, such as certain trees, may not be able to keep up with the rate of adaptation and shift required, depending on the rate of climate change, or may not encounter the conditions necessary (e.g., soil in the northern latitudes) required for migration (Drobyshev et al. 2013). Other existing species or new species could thrive or migrate into the spaces left behind. Projections have difficulty accounting for the cumulative impacts on ecosystems; stresses such as ecosystem fragmentation and pollution will need to be considered, in addition to potential climate-related changes, to fully understand the effects and potential effects of climate change on ecosystems (Nantel et al. 2014; Falardeau and Bennett 2020). The expansion of the mountain pine beetle in Western Canada, as a result of changing temperatures and historical management practices, is a good example of how cumulative impacts, including climate change, can alter ecosystems and result in impacts on ecosystems and the human communities who depend on them for their livelihoods (Mitton and Ferrenberg 2012).

3. IMPLICATIONS FOR THE CANADIAN NORTHERN CORRIDOR

The documented and projected future climate change impacts identified above have implications for future corridor development in Northern Canada. Transportation infrastructure is particularly vulnerable to permafrost thaw and freeze-thaw processes, ice loss and reduced snow cover, climate-related coastal impacts and extreme events. Some climate change impacts on northern transportation infrastructure have already been documented and include coastal erosion affecting built infrastructure in the Beaufort Sea region (Radosavljevic et

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

al. 2016) and permafrost thaw affecting airport infrastructure at multiple airports across Nunavik (Boucher and Guimond 2012). In a recent study, climate change was projected to increase the lifecycle costs of infrastructure in Northern Canada by $4.33 billion by 2059 (Suter et al. 2019). This illustrates the scale and magnitude of the potential impacts of climate change on a northern corridor. In this section, we focus on the implications of climate change impacts for the construction, operation and maintenance of a corridor and the infrastructure within it. We also discuss the implications of global climate change politics for future corridor development.

3.1. CONSTRUCTION

Climate change impacts are likely to affect the construction of transportation infrastructure in a corridor in terms of regulations and design, route planning and potential impacts during construction. Climate change adds layers of complexity to an already complex task of designing and planning large infrastructure developments in Northern Canada. Current and expected changes to the biophysical environment have implications for how and where infrastructure is built, including codes, standards, land-use planning, zoning and other similar instruments (Steenhof and Sparling 2011; Champalle et al. 2013). Ensuring that development within a corridor follows a set of codes and standards that are adapted to current and future climate conditions and adaptable to unexpected change will be critical (ECCC 2016). The example of how one-in-25-year floods are now projected to become one-in-four-year floods in Tuktoyaktuk (Lamoureux et al. 2015) highlights how infrastructure will need to be built for dynamic and increasingly extreme conditions. Current codes, standards and other instruments will need to be evaluated based on location, conditions and type of infrastructure, and may even need to be innovated as a part of corridor development (Steenhof and Sparling 2011). To be effective for adaptation, codes and standards must include future climate change projections, but this is often constrained by the absence of downscaled climate data (Ford et al. 2015).

When planning the corridor route, considerations will need to be made to avoid areas that are highly susceptible to climate change impacts and those with human occupancy. An example of what this could entail is provided by the Arctic Corridors and Northern Voices (ACNV) project that was established to ensure that perspectives and recommendations from 13 communities across the Canadian Arctic were included in the development of the Low Impact Shipping Corridors through the region (Dawson et al. 2020). Through the ACNV, communities along potential corridors provided recommendations on preferred corridors, areas to avoid, seasonal restrictions, areas where vessel modification would be necessary and areas where additional charting was necessary.

Climate change also has the potential to increase the cost of construction and to create risks to equipment and workers. For example, changing climate is affecting the conditions and access needed to construct winter roads in parts of Northern Canada, such as to First Nations in northern Ontario (Hori et al. 2018a). Construction has the potential to add to cumulative impacts and magnify the environmental and socio-economic impacts of climate change. These factors will also need to be considered at finer scales in the development of the corridor concept.

3.2. OPERATION

Climate change impacts could accelerate the deterioration of, and in some instances could severely damage, corridor infrastructure. For example, permafrost degradation can pose a significant threat to natural and built infrastructure (Pendakur 2017; Suter et al. 2019), extreme temperatures can affect the efficiency of electrical lines or pipelines, and can damage railways over time (Dzikowski, Donovan and Happychuk 2017), and extreme events such as forest fires (Figure 5) can completely shut down areas with infrastructure or even key infrastructure hubs, grinding industrial systems to a halt. Emergency monitoring and response have already been recognized as a priority for improvement in the context of climate change and ongoing infrastructure projects in Canada (ECCC 2018) and, in some cases, a lack of capacity to monitor and respond to emergencies has affected the progress of projects. Pipeline and tanker-spill response has been a major concern in the cases of the Northern Gateway and Kinder Morgan's Trans Mountain expansion (TMX) pipeline projects. This will be a challenge for the CNC given its multi-jurisdictional geographic expanse and remoteness. Limited search and rescue capability, minimal bathymetric data for shipping charts and the remoteness of Arctic Canada present particular challenges to shipping and other forms of transport (Ford and Clark 2019; Olson et al. 2019; Dawson et al. 2020). Oil and other hazardous materials that are likely to be transported through the corridor are more difficult to clean up in icy conditions, and natural cleaning processes are impeded by cold water and air temperatures (Crepin, Karcher and Gascard 2017). The characteristics of spill-response and clean-up risks have been examined in areas of Northern Canada (Nudds et al. 2013), but have not comprehensively been examined across the proposed CNC route.

Figure 5: Extreme events that are influenced by climate change could threaten infrastructure in a corridor and create a chokepoint. For example, the remnants of a wildfire show how close the fire came to threatening an electrical transmission corridor through central B.C. (photo credit: David Fawcett)

Climate change impacts could create "chokepoints"[14] in the corridor. Given the remoteness of northern Canadian and the absence of alternative modes of transportation, potential choke points could effectively shut down the corridor. For example, coastal impacts and sea-ice uncertainty could delay or limit shipping capacity at certain times of the year, damage coastal infrastructure or limit route accessibility, especially in the Canadian Arctic (Dawson 2019). Because ports represent key links and chokepoints in supply chains, they are an excellent example of how increasing climate-related impacts could create backlogs throughout the rest of the corridor system. For example, the port of Churchill, Man. is the only deep-water port on Canada's northern coast, making it a key strategic export location. The port is expected to experience increased potential for growth as the open-water season increases with sea-ice loss, but use and maintenance problems on the railbed that supplies the port due to permafrost thaw could create a chokepoint for goods to be transported to the port for export (Ford et al. 2016).

3.3. MAINTENANCE

Climate change will likely increase the costs of maintenance and change maintenance procedures. Maintenance is important to general upkeep and to prevent environmental impacts, to reduce failure during acute climate events and to detect and mitigate failure or impacts from longer-term climate changes (ECCC 2018). It is also an important part of evaluating the performance of climate change adaptations built into infrastructure (Dore et al. 2014). For example,

14 Chokepoints are key junctures in transportation and infrastructure systems that are vulnerable to obstruction due to a variety of factors, often geographic or political (Bailey and Wellesley 2017; Ford et al. 2019).

maintenance would be important to monitor and mitigate against the impacts of freeze-thaw cycles (Andrey and Palko 2017) and the handling of extreme water levels and erosion (Dzikowski et al. 2017). As noted earlier, the replacement costs of infrastructure in Northern Canada is expected to increase by $4.33 billion by 2059 due to climate change; under a high-emissions scenario, replacements costs jump from $12.87 billion (baseline) to $17.19 billion, due to changes caused by climate forcing (Suter et al. 2019). The increasing replacement costs of infrastructure due to climate change represent an increase in the costs related to addressing general wear and tear and hazards, and can include both maintenance or total replacement (Suter et al. 2019). Maintenance is, however, difficult and costly to track, especially over a large geographic area where accessibility may be an issue (ECCC 2018).

3.4. POLITICAL CONSIDERATIONS FOR CNC FEASIBILITY

The politics of climate change are likely to have implications for CNC development. Canada is a signatory of the 2015 Paris agreement, which was ratified in Parliament in October 2016. As a part of the Paris agreement, the Canadian government has agreed to work towards the goal of limiting global temperature increase to less than 2.0 C above pre-industrial levels (Government of Canada 2016). If the CNC will contribute to expanding Canada's GHG emissions, it may contradict Canada's commitment to reducing GHG emissions as outlined in the Paris agreement. Furthermore, in light of the global climate change movement, acquiring the social licence[15] across the entire country that would be necessary for the development of a corridor that is potentially linked to energy production that increases GHG emissions could also be a challenge (see the example of the Kinder Morgan pipeline). Fluctuations in the price of resources like oil and natural gas that would likely be transported through the corridor will also have implications for future corridor development and need to be examined further.

3.5. FUTURE RESEARCH NEEDS

This review highlights some important future research needs. First, improved downscaled models of climate change impacts along the proposed corridor route are needed to understand the potential severity of change for individual areas. This would allow for analyses of potential climate change impacts for particular types of infrastructure along the corridor route and insight into the planning of the corridor route. Second, research is needed to identify how the proposed corridor could affect existing land-use practices, including by local communities and Indigenous Peoples. The United Nations Declaration on the Rights of Indigenous Peoples emphasizes the need for free, prior and informed consent from Indigenous Peoples for a development such as the CNC, especially in light of climate change impacts. It will be important to work with communities to understand current and

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15 More formally known as "social licence to operate" within peer-reviewed literature. Social licence is the acceptance, approval or even acclamation of economic activities (that will typically have some kind of social and/or environmental impact) by various levels of society, including local communities and Indigenous Peoples, as well as broader society (e.g., Canadian society) (Demuijnck and Fasterling 2016).

potential future climate change impacts in their areas as well as implications for future corridor development, drawing on local and traditional knowledge[16] and the best available science. Local communities and Indigenous Peoples need to be involved to discuss if the proposed corridor is desirable and, if so, how it could be constructed to have the least impact on existing human activities and use of the environment, as well as the greatest benefits for local people. Third, the economic viability of the corridor needs to be studied in the context of climate change impacts, GHG-emission-reduction commitments and changes in global market demands for resources that would likely be transported in the corridor (e.g., oil and natural gas). This includes estimating construction, operation and maintenance costs for the corridor under future climatic conditions and the potential costs that climate change politics could have on the corridor.

Key questions could include: how could changing societal perspectives and associated consumption trends at the national and global levels due to concerns about climate change impact the economic sustainability of the CNC if the transportation of oil and gas are key components of its development? Could the corridor and infrastructure within it be adapted to accommodate new forms of energy? How the national and global economies will respond to climate change is uncertain, but it is unlikely to be static (Challinor, Adger and Benton 2017). Therefore, understanding how these factors could affect the corridor may help guide the visioning and design of the CNC and, ultimately, its adaptability to and innovation in response to the impacts of climate change. This research need may present the CNC development with an opportunity for climate mitigation and adaptation innovations that can be exported to other energy-corridor developments.

4.0. CONCLUSIONS

This paper reviews scientific evidence about the potential impacts of climate change in Northern Canada and examines implications for the future development of the CNC, a proposed multimodal transmission corridor. Permafrost thaw, sea-ice loss, extreme weather events and changes in coastal processes (e.g., sea-level rise, erosion), among other impacts, are increasingly being observed in Northern Canada. These impacts threaten the feasibility, construction, operation and maintenance of the proposed corridor and the infrastructure within it. Even under a scenario in which future atmospheric greenhouse gas emissions are low, many of these impacts would persist and could worsen into the foreseeable future. Moving forward, further research into the socio-economic impacts of climate change at local, regional, national and international scales is recommended, to understand how economic shifts in response to climate change could impact the feasibility of the CNC concept. Significant effort will also be required to examine all aspects of climate change impacts, adaptation and vulnerability across scales. This will include

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16 A dynamic set of knowledge, skills and practices of local and Indigenous communities grounded in history and constantly updated based on experiences and cultural and environmental changes. Traditional knowledge is generally transmitted between generations orally (IPCC 2014).

working closely with local communities and Indigenous Peoples along the proposed corridor route, to understand if a corridor is desirable and relevant to them and, if so, whether it can be developed in a manner that sustains livelihoods, culture, health and well-being in a changing climate.

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