Climate Risks & Adaptation Practices

For the Canadian Transportation Sector 2016

Canada

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CLIMATE RISKS AND ADAPTATION PRACTICES FOR THE CANADIAN TRANSPORTATION SECTOR 2016

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CHAPTER 1: INTRODUCTION

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The Earth's climate is changing, and Canada is warming at a faster rate than most regions in the world. From 1950 to 2010, the average annual temperature in Canada has increased by close to 1.5°C, which is approximately double the global average (Bush et al., 2014). This warming trend has been associated with changes to other important climatic variables, including precipitation, sea level, inland water levels, sea ice, permafrost, and extreme weather events (Table 1).

In the coming decades, anthropogenic emissions of greenhouse gases will result in further changes to global and regional climates. These changes have implications for the transportation sector, and the Canadian economy and society more broadly.

The Government of Canada has produced a series of climate change assessments at the national level, which identify observed and expected impacts to Canada's economy, society, and environment; and practices to adapt to these impacts. These include:

- Canada's Marine Coasts in a Changing Climate (2016);
- Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation (2014);
- From Impacts to Adaptation: Canada in a Changing Climate (2007);
- Climate Change Impacts and Adaptation: A Canadian Perspective (2004); and,
- Canada Country Study: Climate Impacts and Adaptation (1997-98).

While these reports indicate that some aspects of transportation are highly vulnerable to changing climatic conditions, adapting infrastructure and operations to a changing climate and emerging environmental conditions remains a relatively new area of focus for the transportation sector.

PURPOSE AND FORMAT OF REPORT

This report is a snap-shot in time, presenting the state of knowledge about climate risks to the Canadian transportation sector, and identifying existing or potential adaptation practices that may be applied to reduce them. It is intended to serve as an accessible source of information that can inform decision-making and policy development, without making recommendations or prescribing specific actions which can vary based on different situations. This report provides transportation decision-makers and practitioners with information intended to support enhanced resilience to climate risks, while also serving as a knowledge foundation for future research.

The report is organized into six regional and one urban chapter to reflect the different climate vulnerabilities, priorities, practices and opportunities across Canada's national transportation system. Each chapter includes a profile of the region's population, economy, climate and transportation networks, in addition to examining observed climate impacts, future risks, opportunities, and adaptation approaches for road, rail, air, and marine transportation.

Climate risks considered within the framework of this report include both changing climate conditions ("slow onset" changes, such as permafrost thaw and sea level changes) and extreme weather events. While it is difficult to attribute a single weather event to climate change, there is growing confidence that some types of extreme events will increase in frequency and/or intensity as the climate continues to warm, and these events represent significant risks to transportation infrastructure and operations.

The development of this report represents a significant and collaborative effort in bringing together the knowledge, expertise and perspectives of the chapter authors and reviewers. Based on available literature, each chapter includes an assessment of peer-reviewed (academic) and grey literature relevant to the transportation-climate nexus in the given region. Furthermore, to round out the knowledge base in cases where existing literature was limited, several chapters also integrate perspectives from transportation practitioners, and are cited as personal communications.

Content that has been deemed out of scope for the purposes of this report includes:

- Impacts on pipelines and power transmission infrastructure;
- Indirect impacts on transportation associated with climate change impacts on other sectors (e.g., agriculture, tourism and recreation, fisheries), and other nations. Interdependencies among municipal sectors are considered in Chapter 9;
- Disaster and emergency management practices; and
- The impact of transportation on the climate (e.g., greenhouse gas emissions) and climate change mitigation activities.

Collectively, these features have shaped the unique content found in the chapters. For example, the Urban Chapter emphasizes transportation planning approaches; the British Columbia and Northern chapters provide greater detail on engineering practices and extreme precipitation risks; and the Prairies Chapter incorporates content on practitioner experiences and adaptations within the trucking industry. The Synthesis chapter attempts to bring these regional and urban perspectives together to capture the state of knowledge at the national level on climate risks and adaptation practices for Canada's transportation system.

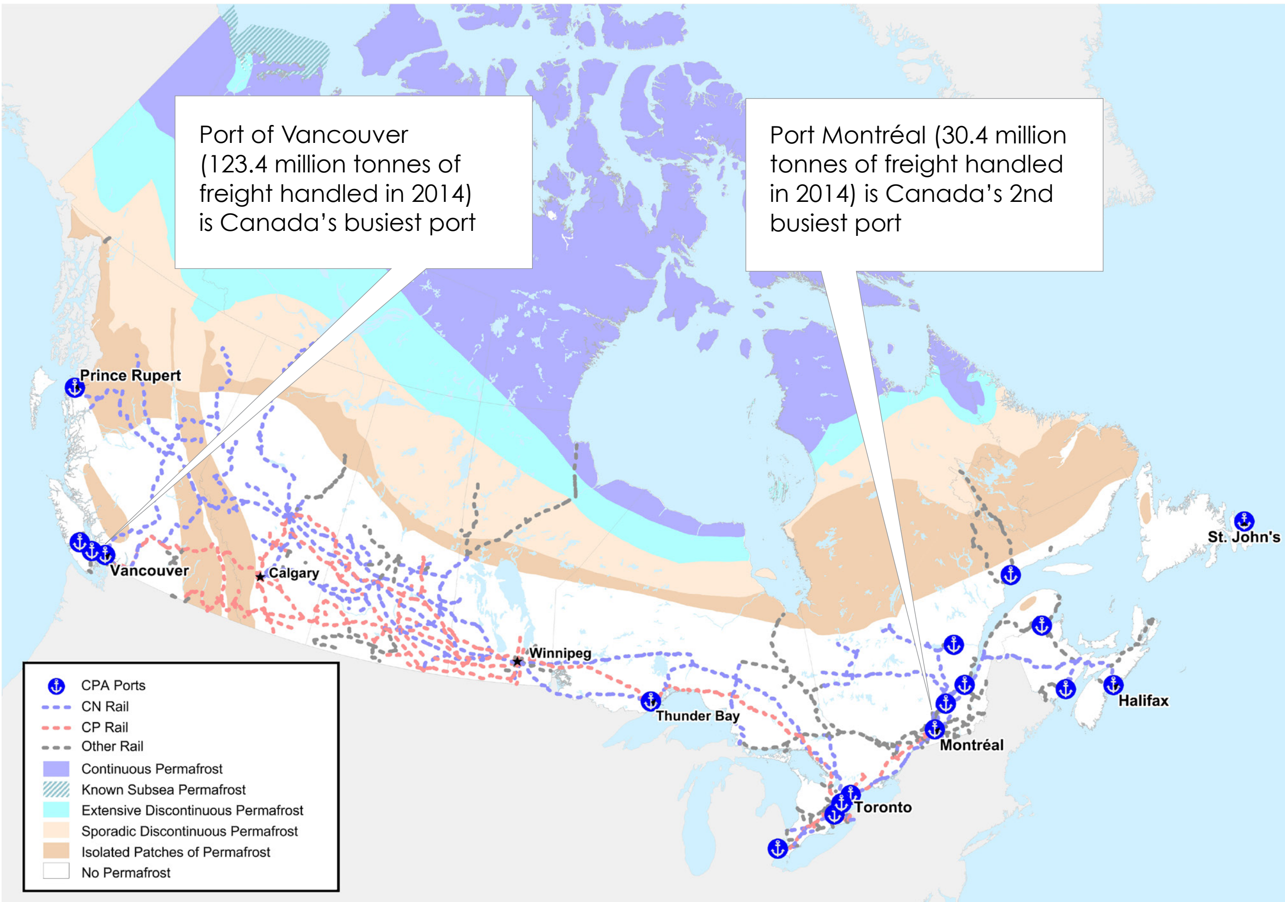
CANADA'S TRANSPORTATION SYSTEM

Canadians depend on transportation services for day-to-day travel, and for the movement of resources and goods vital to the economy. Canada's communities and markets are widely dispersed, spanning a distance of more than 5,000 km from east to west and 4,500 km from north to south. Industries such as manufacturing, energy, mining and agriculture, as well as services such as healthcare and retail trade, all depend on the reliable functioning of the transportation system.

All modes of transportation, each with its own unique characteristics, play specific roles in local, national, and international movements (Figure 1 and Figure 2). As a whole, the Canadian transportation system (including highways, railways, airports, ports, and associated facilities) moved over $1.04 trillion of merchandise trade in 2014 (Transport Canada, 2015).

Transportation is jointly governed by Canada's federal, provincial, and municipal governments. Generally, the federal government oversees international and interprovincial transportation (including aviation, marine, and rail); provincial governments are responsible for intra-provincial transportation (including highways); and municipal governments are responsible for managing urban transportation (including transit and local roads). The private sector also plays an important role as owners, operators, and managers of infrastructure and assets, including rail infrastructure, vehicles, ships, and aircraft.

Figure 1: System overview of the Canadian Port Authorities, Great Lakes and National Rail Network, including key trade and passenger statistics for marine and rail transport.



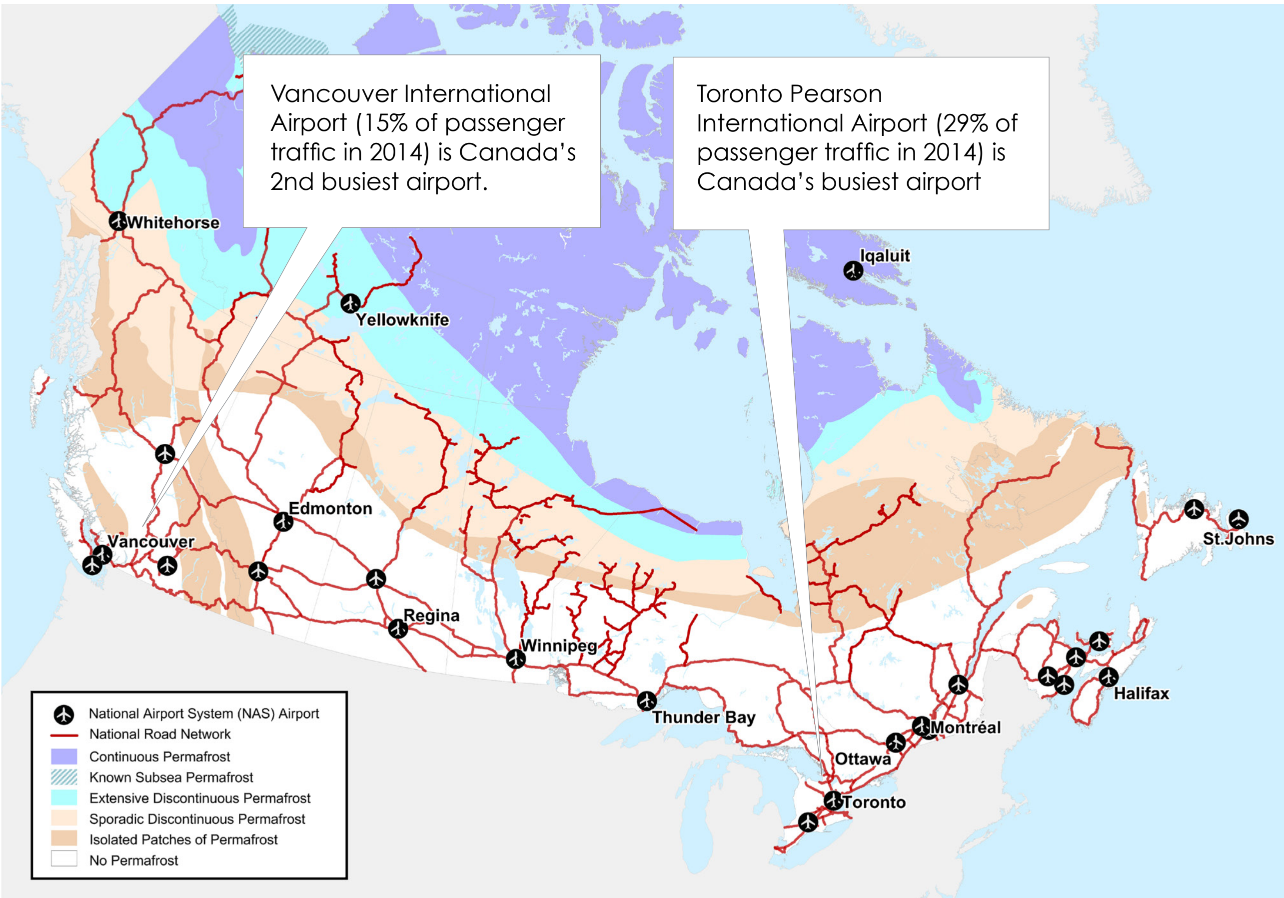
Canada's Rail System

- 320.2 million tonnes of freight shipped by rail (2014)
- $126.2 billion in rail international trade traffic (2014)
- 45,742 route-kilometres (km) of track:
  - CN owns 49.2% (22,517 km)
  - CP owns 26.1% (11,927 km)
- VIA Rail moved 3.77 million passengers (2014)

Canada's Port System

- 567 port facilities, 902 fishing harbours and 202 recreational harbours
- 62% of total tonnage handled by the 18 Canadian Port Authorities
- Great Lakes/St. Lawrence Seaway System serves 15 major international ports and 50 regional ports that connect to 40 provincial/interstate highways and 30 rail lines

Figure 2: System overview of the National Airport System and National Highway System, including key trade and passenger statistics for aviation and road transport.



Canada's Aviation System

- 647 Canadian air carriers
- 26 NAS airports handled around 90% of total air passenger traffic (2014)
- 1.1 million tonnes of freight unloaded at Canadian airports (2014)

Canada's Road System

- > 1.3 million kilometres of public road in Canada
  - 34% is paved
- Canada's largest transportation sector
  - > 62,000 trucking businesses in operation
- $371 billion in trucking traffic between Canada and the U.S. (2014)

OBSERVED AND PROJECTED CHANGES TO CANADA'S CLIMATE AND HYDROLOGY

Canada has experienced a number of changes to climate variables affecting the transportation sector, including temperature, precipitation, permafrost, relative sea level, sea, lake and river ice, inland water levels, and extreme weather events; and further changes to these variables are projected (Table 1).

Table 1: Summary of observed and projected changes to climate and hydrological variables relevant to the Canadian transportation system. (Source: Warren and Lemmen, 2014; other sources as indicated)

Variable	Observed Changes	Projected Changes
Temperature	**Canada has become warmer.** • The average air temperature has increased by 1.5°C during the period from 1950 to 2010. • Hot summer days have become more frequent since 1950, while the frequency of cold nights has decreased, nationally.	**Canada will continue to warm.** • Warming will be greatest in winter, with the largest temperature increases projected in northern Canada. • The magnitude of projected warming varies substantially with the emission scenario. • Unusually warm days are projected to occur more often throughout the 21st century, while unusually cold days and nights will become less frequent. • Heat waves are projected to become longer, more frequent and more intense. By mid-century, a one-in-20-year extreme hot day is projected to become about a one-in-5 year event over most of Canada.
Precipitation & Snow Cover	**Canada has generally become wetter.** • Annual average precipitation has increased in recent decades. • Annual snowfall has declined over most of southern Canada and increased in the north over the last 6 decades.	**Most of Canada will continue to get wetter, with regional differences in seasonal patterns.** • Precipitation may decline in summer and fall in parts of southern Canada. **Most of Canada will see less snow cover.** • Snow cover is projected to decrease in southern Canada (especially the west coast mountains), while it is projected to increase in northern Canada due to increased precipitation. **Heavy precipitation events are projected to occur more often.** • Rare extreme precipitation events are projected to occur about twice as often by mid-century over most of Canada, relative to the period from 1950 to 2010.
Permafrost	**Permafrost has warmed.** • Permafrost temperatures at many sites across Canada have increased over the past two to three decades.	**Permafrost is projected to continue to warm at higher rates than those observed to date.** • It will take many decades to centuries for colder permafrost to completely thaw.

Variable	Observed Changes	Projected Changes
Relative Sea Level	**Sea levels have changed in Canada.** • Relative sea level has been rising in Atlantic Canada and the Beaufort Sea (over 3 mm/year), and on the Pacific coast to a lesser extent. (Average global sea level rose 1.6 mm/year between 1880 and 2012). • Where sea level has risen, storm surges and coastal erosion have been amplified (Atkinson et al., 2016). • Relative sea level has been falling in areas where land has been rising due to post-glacial rebound. Relative sea level has declined about 10 mm/year around Hudson Bay.	**Sea levels will continue to change.** • Estimates of future changes in global sea level by the year 2100 range from a few tens of centimetres to more than a metre. • Projected changes in Canada range from increases of up to 100 cm on the Atlantic, Pacific, and Beaufort coasts, to decreases of almost 100 cm in the central Arctic.
Sea Ice	**Arctic sea ice extent has decreased significantly.** • Minimum ice extent at the end of summer has declined by 13% per decade over 1979-2012. Maximum winter sea ice extent has declined by 2.6% per decade. • Ice cover has become increasingly dominated by thin first-year ice, with significant reduction in the extent of thick multi-year ice. • Winter sea ice has also declined in the Labrador-Newfoundland and Gulf of St. Lawrence region.	**The extent and thickness of sea ice in the Canadian Arctic will continue to decrease.** • Some models project a nearly ice-free summer before mid-century in the Arctic Ocean. Summer sea ice may persist longer in the Canadian Arctic Archipelago region.
Lake and River Ice	**Ice cover duration has been decreasing.** • Most of Canada has seen trends towards earlier ice-free dates (lakes) and ice break-up dates (rivers) since the mid-20th century, and this trend is particularly evident in Western Canada.	**Duration of ice cover is projected to continue to decrease.** • Earlier break-up dates and later freeze up dates are projected to decrease ice cover duration by up to a month by mid-century.
Inland water levels	**Inland water levels have been highly variable with episodes of lower than normal levels.** • Great Lakes Water levels were below long-term averages from 1997 to 2012 (Shlozberg et al, 2014) but higher than normal in 2013 and 2014. (Dorling and Hanniman, 2016; Great Lakes Environmental Research Laboratory, 2015).	**Inland water levels are expected to continue to fluctuate, with a projected trend towards lower water levels.** • Episodes of low water levels are projected to occur more frequently in some freshwater bodies (e.g., the Great Lakes and Mackenzie River). • Some models project decreases in water levels of 0.5 to 1 m in the Great Lakes and St. Lawrence River by 2055 (Shlozberg et al, 2014; Brown et al., 2012).

SENSITIVITIES OF CANADIAN TRANSPORTATION TO CLIMATE

All transportation systems are climate-sensitive. These sensitivities can translate into infrastructure damage and deterioration, disruptions to transport operations, and unsafe conditions. Some of the most vulnerable components of Canada's transport system are integral to remote and resource-based communities in the North. However, a changing climate and extreme weather will affect all modes of transportation in every Canadian region.

Transportation's sensitivities to climate and extreme weather are illustrated by the impacts of acute weather events in recent years. For example, Canada's costliest disaster – the June 2013 floods in Alberta – resulted in an estimated $6 billion in damages and recovery costs, and saw 1,000 km of roads destroyed and hundreds of bridges and culverts washed out. Similarly, the July 2013 flash flood in the Greater Toronto Area, which is considered to be the most expensive natural disaster in Ontario, caused major transit delays, road closures, and flight cancellations (Environment Canada, 2014).

EXTREME WEATHER TRENDS

Trends in extreme precipitation events have been difficult to identify from climate data, due to spatial variability in precipitation patterns. However, insurance data demonstrates that natural disasters have been increasing in Canada, including events associated with flooding, wind, and wildfires (Institute for Catastrophic Loss Reduction, 2012).

While many factors, other than climate change, contribute to rising insurance losses (including exposure of property, increasing wealth, and aging infrastructure), this trend demonstrates a pattern of infrastructure vulnerability in Canada to extreme weather events (Warren and Lemmen, 2014).

Extreme weather events are not the only climate risk to transportation. Other risks to the Canadian transportation system, associated with a changing climate, include the following:

- Temperature changes and fluctuations contribute to infrastructure deterioration and operational challenges, especially in permafrost regions of northern Canada, but also across southern Canada due to changing freeze-thaw cycles during the winter and heat waves during the summer.
- Changing ice conditions affect marine operations and vessel navigation, especially in northern Canada, with broad implications (both positive and negative) for economic development, trade, and security.
- Sea level rise and storm events can increase risks of coastal erosion, flooding, and associated damage, with implications for transportation infrastructure and operations in coastal areas of Canada.
- Low inland water levels (particularly in the Great Lakes) can reduce vessel capacity, and create navigation difficulties.

ADAPTATION OPTIONS

Adaptation options for transportation may include engineering and technological solutions, as well as policy, planning, management, and maintenance approaches. Some examples, from the chapters in this report, include:

- Changing pavement mixes for roads, for example using more heat-tolerant pavements;
- Expanding drainage capacity for infrastructure, including culvert size;
- Increasing maintenance, including clearing debris from culverts to reduce flooding risks, and clearing snow to preserve permafrost stability under vulnerable roads;

- Implementing heaters and cooling fans to improve tolerance of traffic signal controllers to extreme temperatures, and thermosyphons to maintain permafrost stability at airports;
- Changing infrastructure design requirements to include climate change considerations or to introduce new flood event thresholds;
- Elevating or relocating new infrastructure where feasible;
- Changing engineering procedures, such as increasing temperature thresholds for rail track to reduce risk of buckling during large temperature differentials;
- Increasing monitoring of weather events and infrastructure conditions;
- Implementing or enhancing travel advisories and alerts to communicate travel conditions and service delays during weather events.

There are two categories of response to climate change – mitigation and adaptation.

Mitigation refers to human interventions to reduce greenhouse gas emissions.

Adaptation refers to any activity that reduces the negative impacts of climate change and/or takes advantage of new opportunities. This includes actions taken before impacts are observed (anticipatory), and after impacts have been felt (reactive). Adaptation can be planned (i.e., the result of deliberate policy decisions), or spontaneous, in the case of reactive adaptation (Warren and Lemmen, 2014).

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2 · Synthesis

CHAPTER 2: SYNTHESIS

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Transportation plays a critical role in the movement of goods and people in Canada, supporting all sectors of the economy and Canadians' quality of life. The effects of a changing climate and extreme weather present both risks and opportunities to transportation infrastructure and operations. How Canadians adapt to these changes will be important to ensure the continued prosperity of our nation.

This Synthesis summarizes findings from the seven core chapters of the report *Climate Risks and Adaptation Practices for the Canadian Transportation Sector 2016*, and presents examples of regional climate impacts, specific modal impacts (e.g., road, rail, marine, air and urban systems), and adaptation approaches being undertaken across Canada. (References for the examples presented in this chapter appear throughout the report.)

The following present high-level conclusions from the report:

- **Transportation infrastructure, essential to Canada's domestic and international trade, is vulnerable to damage and disruptions from a changing climate and extreme weather, and this can pose risks to other sectors of the economy.** Studies are underway to better understand these vulnerabilities, and adaptive practices are being undertaken to reduce future impacts. Regional chapters provide further details on initiatives related to the Great Lakes-St. Lawrence Seaway, the Chignecto Isthmus (highway and rail), Port Metro Vancouver, Port Saint John, and other trade infrastructure.

- **Climate and weather-related delays and disruptions to passenger travel could become more frequent in future.** These events can temporarily isolate remote communities in northern regions, which may rely on a single highway or airport for connectivity, and lead to costly damages and travel disruptions for large urban areas. Redundancies in transportation systems (allowing multiple methods of travel) are one method to reduce these impacts.

- **Northern transportation systems are experiencing some of the greatest impacts from warming, and temperatures will continue to increase at a faster rate than any other region in Canada.** Degrading (thawing) permafrost has caused damage to roads, railways, and airport taxiways and runways, and will continue to pose risks to transportation safety, efficiency, and maintenance budgets in the North. The operating windows and capacities of some winter (ice) roads have also shortened in recent years, resulting in the need for alternative methods of shipping.

- **A changing climate is expected to result in some opportunities for Canadian transportation.** Potential benefits include longer marine navigation and construction seasons, reduced winter maintenance, greater operating efficiency for rail, and improved fuel efficiency for all modes. Melting sea ice is also slowly opening up arctic waters to new navigation routes, however, the increased mobility of summer sea ice, as well as increased coastal erosion and storm surge flooding, present ongoing difficulties for shipping, exploration, and associated coastal infrastructure.

- **Reactive approaches to managing climate risks (e.g., responding to past impacts or events), remain common in Canada's transportation sector. At the same time, examples can be found in all regions, and for all transportation modes, of actions being taken in anticipation of future climate conditions.** Many owners and operators, both public and private, have adapted their operations based on investigations and lessons learned from past weather-related events. Transportation decision-makers are also more frequently engaging in pro-active planning.

- **Transportation decision-makers are increasingly adopting a risk management approach to reduce climate risks to their infrastructure and operations.** A variety of specific practices are being used to enhance climate resilience of transportation systems, including integration of climate considerations into organizational planning, policy and design changes, risk and vulnerability assessments, structural and physical adaptations, smart technologies and operational and maintenance changes.

REGIONAL CLIMATE RISKS

While there is considerable variation in Canada's climate, transportation systems across the nation share many of the same climate risks; practitioners can therefore learn from each other's experiences. Risks common to all regions include extreme weather events (particularly heavy precipitation) and extreme and fluctuating temperatures. Extreme events have affected communities across the country, including large urban centres, costing billions in disaster-related losses. Provinces and territories with marine coasts face common risks associated with storm surge flooding, sea-level changes, and coastal erosion. Canada's northern regions, including the three territories and the northern parts of several provinces, all face risks associated with thawing permafrost.

Examples of past impacts to each region's transportation system from climate change and extreme events are depicted in Figure 1. These impacts are characteristic of many, though not all, of the future risks these regions face.

Figure 1. Examples of past impacts to each region's transportation system from climate change and extreme events. (Sources: Ontario – The Arthur M. Anderson unloading at Huron, Ohio, November 29, 2008, By Zars[2]/CC BY- SA 3.0, from Wikimedia Commons; Urban Canada – Frank Frigo, City of Calgary; sources of other photos can be found in other chapters)

2 https://commons.wikimedia.org/wiki/File:AMAnderson.jpg

MODE-SPECIFIC IMPACTS

Similar to regional climate risks, Canada's four major modes of transportation – road, rail, marine, and air – share many common risks to their infrastructure and operations. Furthermore, due to the integration of transportation modes and their physical proximity to one another, weather impacts that adversely affect one mode of transportation tend to have negative impacts on others. An example is the history of simultaneous and sequential failure of highways and rail lines in British Columbia, which often run in parallel along mountain corridors and rivers.

Each transportation mode also faces unique risks. The sections below depict some of the ways that climate and weather can affect road, rail, marine, air, and urban transport systems in Canada, based on the findings in this report. (Note: Drawings are for illustration purposes only and not intended to be technically accurate).

ROAD TRANSPORT

Climate and weather-related impacts on road transportation (Figure 2) can compromise safety and efficiency, disrupt operations, and increase maintenance and operational costs. Anticipated changes to some climate variables can also provide benefits to road transport. For example, warmer winter temperatures can lead to greater fuel efficiency for vehicles, longer construction seasons, and reduced winter maintenance requirements.

Figure 2: How climate and weather can affect road transport. (Illustration created by www.soaringtortoise.ca)

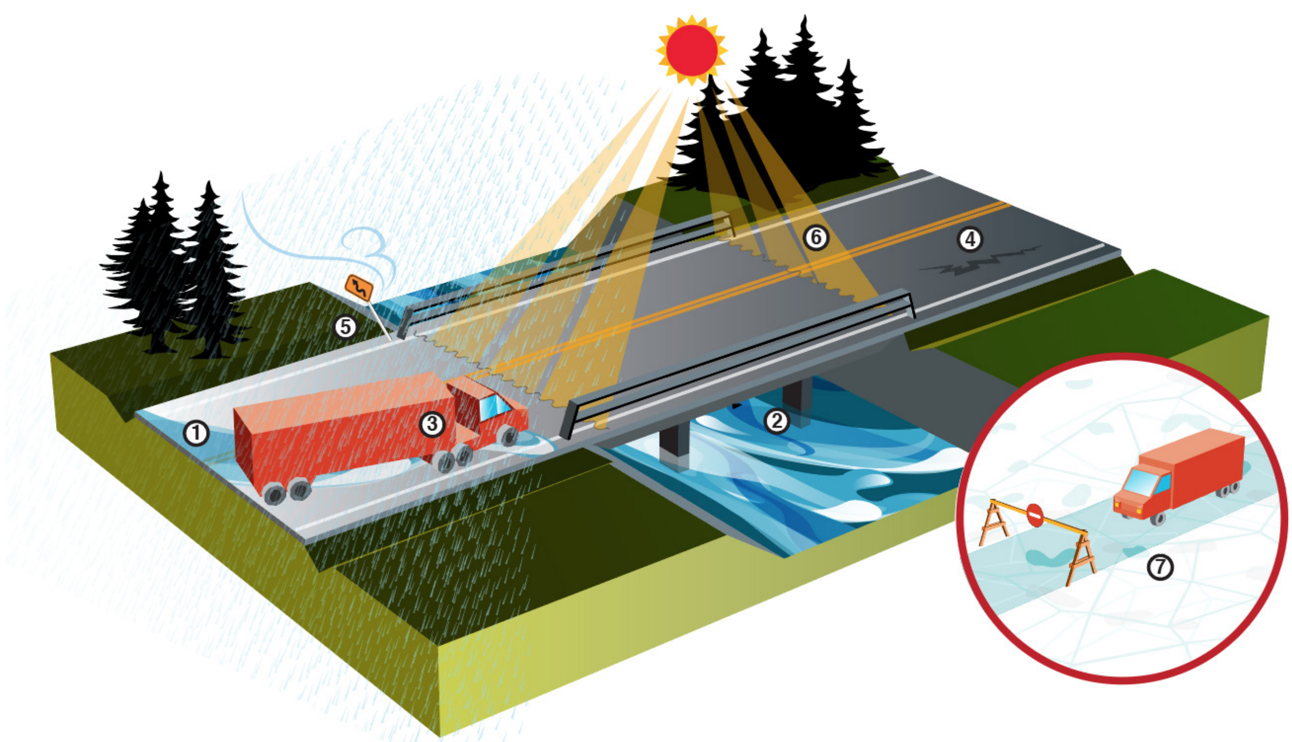


Table 1: Examples of direct impacts on road transportation from various climate factors.

	EXAMPLES OF CLIMATE IMPACTS ON ROAD TRANSPORT	CLIMATE FACTOR(S)
①	**Flooding, damage, and wash-outs of roads and bridges**	• Extreme precipitation (heavy rainfall) and associated standing water, landslides, mudslides, ice-jam flooding, debris floods • Storm surges/sea level rise in coastal areas
②	**Bridge scour**[1]	• Extreme precipitation (heavy rainfall, flood-induced erosion)
③	**Reduced vehicle traction / stability, visibility issues**	• Extreme precipitation • Freezing rain • High winds (including blowing snow)
④	**Damage and deterioration of roads**	• High temperatures (pavement softening, rutting, flushing, bleeding) • Freeze-thaw cycles (pavement deformation, shearing, deterioration) • Warming and thawing of permafrost (ground settlement, slope instability, drainage issues, cracking) • Extreme precipitation (weakened embankments, depressions)
⑤	**Damage to road structures (including signage and traffic signals), obstructions (i.e. fallen power lines/ trees), bridge closures**	• High winds • Extreme precipitation • Freezing rain
⑥	**Thermal expansion of bridge joints, potentially resulting in "blow ups"**	• High temperatures
⑦	**Reduced integrity of winter roads, shortened operating season**	• Warming temperatures

[1] Scour refers to the erosion of sediment at the base of bridge piers, abutments and other underwater structures

RAIL TRANSPORT

Similar to road transportation, the safety, efficiency, and reliability of rail transportation can be compromised by the climate impacts illustrated in Figure 3. Extreme precipitation and coastal storm surges can cause washouts, while both permafrost degradation and temperature extremes can necessitate slower train speeds and potentially cause derailments. At the same time, warming winter temperatures, which are projected throughout Canada, may reduce track and mechanical issues caused by extreme cold.

Figure 3: How climate and weather can affect rail transport. (Illustration created by www.soaringtortoise.ca)

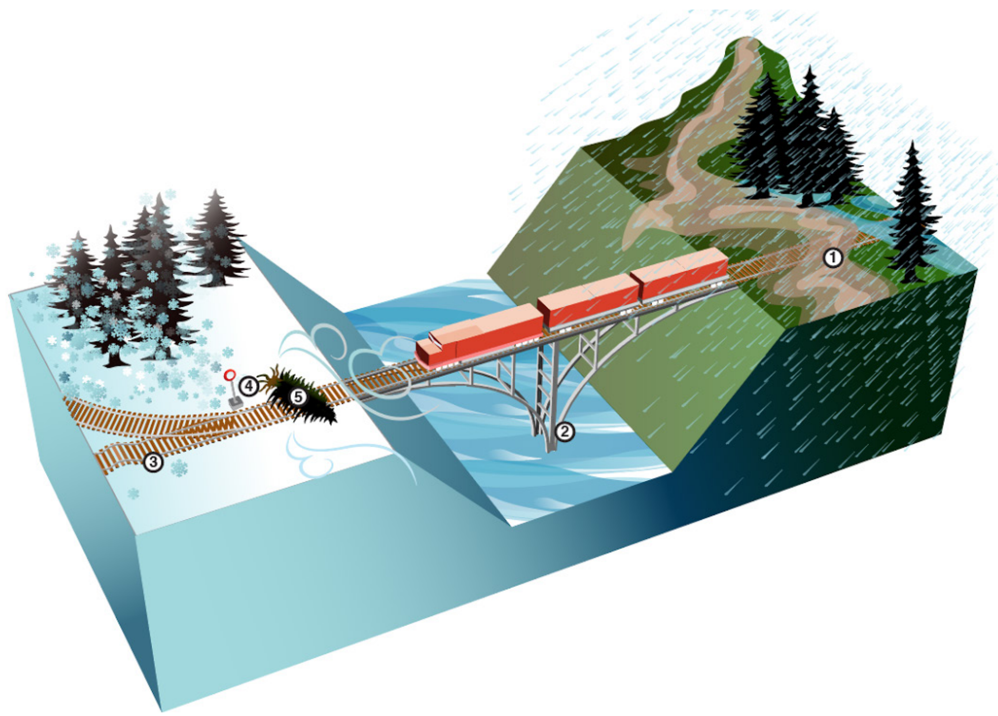


Table 2: Examples of direct impacts on rail transportation from various climate factors.

	EXAMPLES OF IMPACTS ON RAIL TRANSPORT	CLIMATE FACTOR(S)
①	**Flooding, wash-outs, and obstructions of railway tracks and embankments, bridges, and culverts, flooding of below-grade tunnels**	• Extreme precipitation (heavy rainfall) and associated standing water, landslides, mudslides, rock slides, debris floods, ice-jam flooding • Storm surges/sea level rise in coastal areas
②	**Rail bridge scour and damage to bridge structures from ice jams**	• Extreme precipitation (heavy rainfall, flood-induced erosion)
③	**Buckling of rail tracks**	• Permafrost thaw • Extreme heat or large temperature fluctuations
④	**Broken rail tracks and equipment malfunctions and failures (may include broken wheels, reduced effectiveness of brakes, frozen switches)**	• Extreme cold
⑤	**Damage to signalization equipment, rail line obstruction (i.e. fallen power lines/trees), railcar blow-over**	• High winds • Extreme precipitation • Freezing rain

AIR TRANSPORT

Many of the impacts to air transport illustrated in Figure 4 can lead to flight delays, diversions and cancellations. Few accidents are caused by weather conditions in the absence of other contributing factors. Instrument landing systems and other innovations allow aircraft to fly safely in difficult weather conditions, and aircraft are grounded in conditions considered unsafe for flight. Climate risks to airport infrastructure tend to present greater challenges for smaller airports in Canada, which lack the same technologies and resources as larger airports.

Figure 4: How climate and weather can affect air transportation. (Illustration created by www.soaringtortoise.ca)

Table 3: Examples of direct impacts on air transportation from various climate factors.

	EXAMPLES OF IMPACTS ON AIR TRANSPORT	CLIMATE FACTOR(S)
①	**Flooding of airport runways/taxiways, and damage to airport structures and equipment**	• Extreme precipitation (heavy rainfall) and associated standing water • Storm surges/sea level rise in coastal areas
②	**Damage to runways, taxiways**	• High temperatures (pavement softening, rutting, flushing, bleeding) • Freeze-thaw cycles (pavement deformation, shearing, deterioration) • Warming and thawing of permafrost (ground settlement, slope instability, drainage issues, cracking) • Extreme precipitation (weakened embankments, depressions)
③	**Damage to terminals and navigation equipment**	• High winds • Extreme precipitation
④	**Decreased traction on runways**	• Extreme precipitation • Freezing rain
⑤	**Reduced "lift" in aircraft during take-off (plane requires more fuel or must carry less weight)**	• Extreme high temperatures
⑥	**Aircraft not able to take-off or land**	• Extreme fog (low visibility) • Wind (strong cross-winds/tailwinds affect some runways)
⑦	**Operational impacts (equipment malfunction and failure, occupational health and safety issues)**	• Extreme temperatures (heat and cold)
⑧	**Increased use of pavement de-icers (runways) Increased use of aircraft de-icing and anti-icing**	• Changing precipitation conditions

MARINE TRANSPORT

The impacts illustrated in Figure 5 can disrupt marine transportation and compromise the efficiency of port and shipping activities. For example, lower water levels on inland waterways can reduce the cost-effectiveness of marine shipping by decreasing the capacity of vessels, and result in a shift to other ports or other modes of transportation. Hazards to marine navigation from changing ice conditions and storm events can pose safety risks. Ports along Canada's Atlantic and Pacific coasts are subject to impacts from sea level rise and storm surges, and some may also be vulnerable to coastal erosion. Warming temperatures can result in opportunities for marine transport, including a longer operating season and potentially open up shipping routes in Arctic waters, however, this is tempered by continuing challenges to navigation and safety posed by mobile summer sea ice and older, thicker ice.

Figure 5: How climate and weather can affect marine transportation. (Illustration created by www.soaringtortoise.ca)

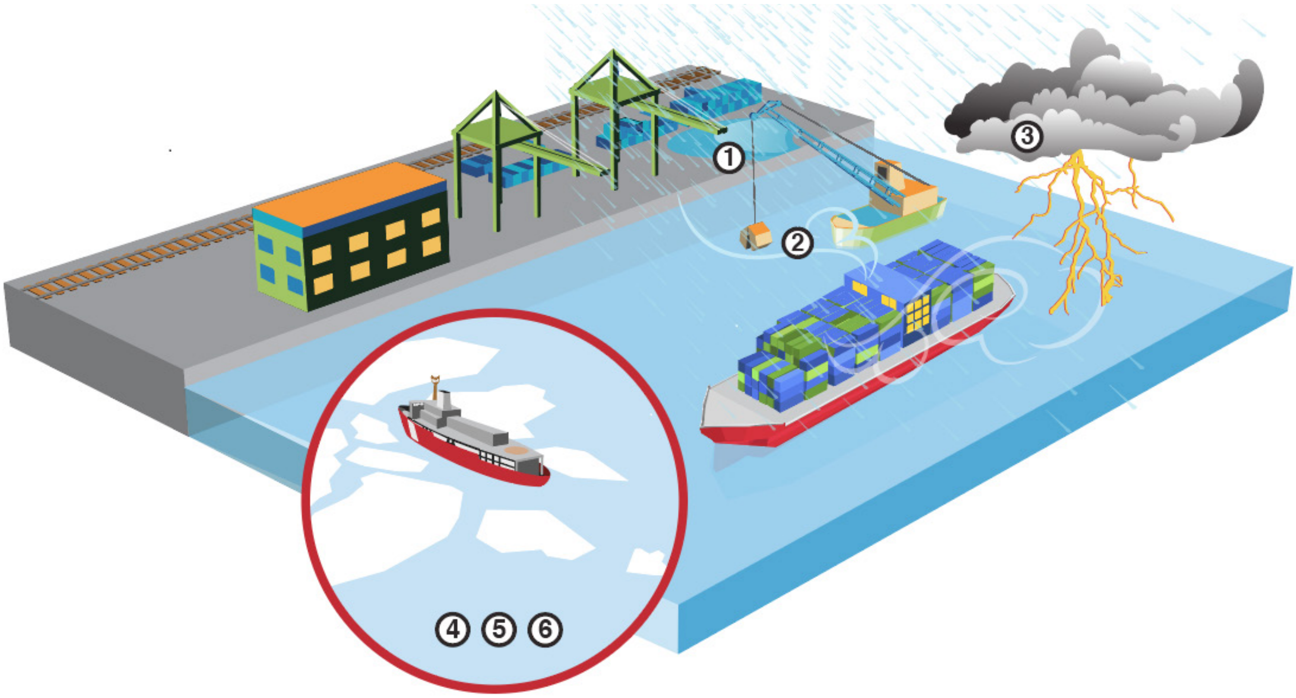


Table 4: Examples of direct impacts on marine transportation from various climate factors.

	EXAMPLES OF IMPACTS ON MARINE TRANSPORT	CLIMATE FACTOR(S)
①	**Flooding and/or damage to port facilities**	• Extreme precipitation (heavy rainfall) and associated standing water • Storm surges/sea level rise, erosion in coastal areas • Freezing rain (ice-scour damage on dock structures and visual navigational aids) • Low water levels (damage and accelerated decay of exposed infrastructure)
②	**Increased or reduced access to ports, dredging requirements**	• Increasing sea levels (e.g., Atlantic Canada and British Columbia) permitting entry of heavier vessels (deeper drafts) • High water levels inhibiting passage of vessels under bridges • Decreasing sea levels (e.g., Hudson Bay) and lower freshwater levels (e.g., Great Lakes) inhibiting access by heavier vessels
③	**Hazards to vessel navigation – storms and wind events (waves)**	• Wave action (difficulty maneuvering vessels) • Melting sea ice (open water worsening the impact of storms and wind events)
④	**Hazards to vessel navigation – detached sea ice**	• Melting ice (detached sea ice moving into unexpected areas)
⑤	**Longer or shorter shipping season**	• Earlier ice break-up/later freeze-up (longer navigation season), later ice break-up/earlier freeze-up (shorter season)
⑥	**New navigation opportunities**	• Melting sea ice (creating open water where navigation was previously not possible)

URBAN TRANSPORT

Impacts to urban transportation systems (Figure 6) include many of the same issues and opportunities identified for road and rail systems in the sections above. Risks more unique to urban systems are associated with underground transit systems and electrical systems. Weather-induced shifts between modes of passenger transport are also more relevant in an urban context. For example, extreme temperatures, precipitation, and strong winds all reduce the percentage of trips taken by walking or cycling.

Figure 6: How climate and weather can affect urban transportation. (Illustration created by www.soaringtortoise.ca)

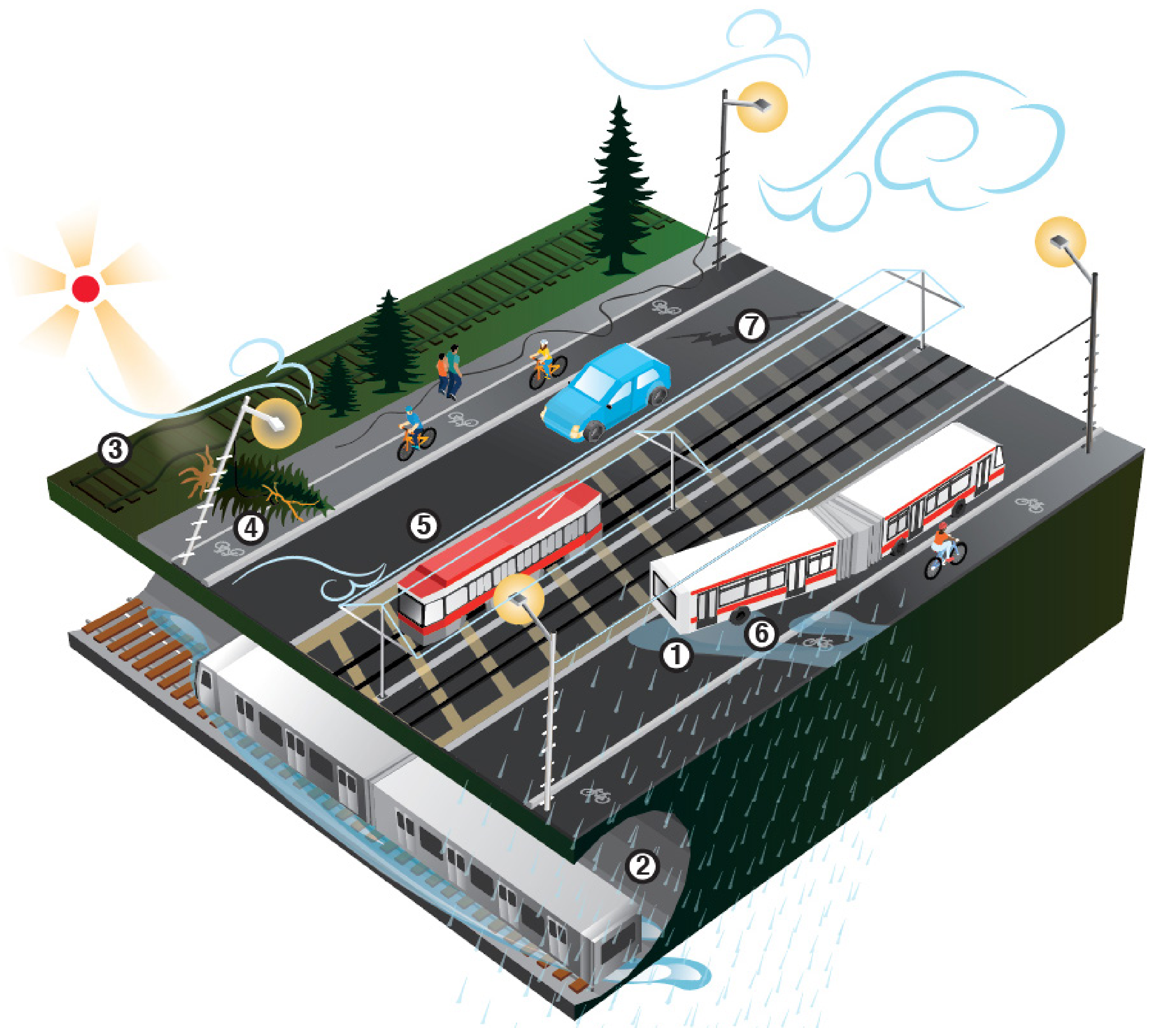


Table 5: Examples of direct impacts on urban transportation from various climate factors.

	EXAMPLES OF IMPACTS ON URBAN TRANSPORT	CLIMATE FACTOR(S)
①	**Flooding, damage, and wash-outs of surface infrastructure (e.g., culverts, roads, sidewalks, bicycle paths)**	• Extreme precipitation (heavy rainfall) and associated drainage issues, ice-jam flooding • Storm surges/sea level rise in coastal areas
②	**Flooding of underground transit systems (e.g., subway tunnels)**	• Extreme precipitation (overloading drainage systems) • Extreme cold (cracking water mains)
③	**Buckling of rail transit lines**	• Extreme heat or large temperature fluctuations
④	**Damage to traffic signals, signage, fallen power lines, trees obstructing routes**	• High winds • Extreme precipitation • Freezing rain
⑤	**Loss of power (overhead electricity for streetcars/trolleybuses, traffic signals)**	• Extreme precipitation • High winds • Freezing rain • Extreme heat
⑥	**Reduced traction/stability of vehicle, visibility issues**	• Extreme precipitation • Freezing rain • High winds (including blowing snow)
⑦	**Damage to and deterioration of roads and bridges**	• High temperatures (pavement softening, rutting, flushing, bleeding) • Freeze-thaw cycles (pavement deformation, shearing, deterioration) • Warming and thawing of permafrost (ground settlement, slope instability, drainage issues, cracking) • Extreme precipitation (weakened embankments, depressions, bridge scour)

ADAPTATION APPROACHES

Transportation owners and operators are using a variety of different approaches to reduce climate risks, including:

- **Integrating climate considerations into organizational planning, policies and designs** - known as "mainstreaming", this refers to the practice of systematically considering climate risks in broader organizational plans and requirements.

- **Undertaking risk and vulnerability assessments -** processes that assess the vulnerability of transportation infrastructure and operations to climate change and associated risks. Results can inform investments and operational decisions.

- **Implementing structural and physical (engineering) adaptations** - solutions that enhance the physical resiliency of transportation networks or infrastructure components. In some cases, structural adaptations are part of broader climate adaptation strategies and programs.

- **Integrating smart technologies** - monitoring and communications technologies and tools, these can provide climate and weather data to support adaptation decision-making, and allow real-time monitoring of asset conditions.

- **Changing operations and maintenance practices** - this category of approaches is often the most cost-effective to implement.

Examples of each of these adaptation approaches are identified below (Table 6) based on chapter findings. This list provides concrete examples of adaptation actions being implemented across Canada.

Table 6: Examples of adaptation approaches identified in this report.

Adaptation Activities	Chapter Reference(s)
Organizational planning, policies and designs	
The BC Ministry of Transportation and Infrastructure requires infrastructure design work to consider climate change adaptation, and has developed a set of notional best-practices.	British Columbia
TransLink, Vancouver's regional transportation authority, has integrated responsibility for climate change risks into its financial management processes.	Urban
Port Saint John's long-term port modernization plans are accounting for sea level rise.	Atlantic
Jurisdictions, such as the City of Sept-Îles are using zoning requirements to control coastal land use and are undertaking cost-benefit analysis for threatened structures.	Quebec
Several jurisdictions are updating design flows and return periods for stormwater management networks, including culverts, to account for an increased frequency and/or magnitude of heavy precipitation events in the future.	Prairies Ontario Atlantic
Structural and physical (engineering) adaptations	
The New Brunswick Department of Transportation rebuilt and raised a bridge on the main road into Pointe-du-Chêne to accommodate future sea level rise scenarios.	Atlantic
The Quebec Ministry of Transportation has oversized the diameter of culverts by 10% to help manage heavy precipitation events.	Quebec
Norman Wells Airport and Ottawa International Airport have grooved their runways to improve traction and drainage during heavy precipitation.	Northern Ontario
Transportation practitioners are implementing and testing engineering techniques, such as thermosyphons, to reduce permafrost thaw under infrastructure, and are using fiber optic technologies to monitor permafrost degradation.	Northern Quebec
Roads in Ontario are using the "SuperPave" system to determine optimal pavement mixtures for local temperature conditions.	Ontario
GO Train engineers are increasing the preferred rail-laying and rail-distressing temperatures for track, in order to reduce buckling risks to rail lines from high temperatures.	Ontario
Risk and vulnerability assessments	
The Greater Toronto Airport Authority (GTAA), the BC Ministry of Transportation and Infrastructure, municipalities, and others have used the Public Infrastructure Engineering Vulnerability Committee's (PIEVC) Engineering Protocol to assess transportation infrastructure (see Box).	British Columbia Prairies Ontario Atlantic
Marine transportation companies have conducted winter-operation risk assessments and ship-specific winterization procedures to reduce risks posed by changing ice conditions in Arctic waters.	Northern
Railway companies are undertaking vulnerability assessments and GIS mapping of areas at risk from landslides, washouts, and other natural hazards.	British Columbia Prairies

Adaptation Activities	Chapter Reference(s)
Smart technologies	
Provinces are using Road Weather Information Systems (RWIS) to inform operations and maintenance, trucking firms are monitoring real-time weather events in their networks to enable efficient re-routing.	Prairies Ontario
Wind sensors are being installed on some rail bridges, allowing rail operators to delay passage or adjust speeds, in the Greater Toronto Area, Metrolinx and GO Transit have installed flood sensors in transit corridors.	Prairies Urban
Railway companies are actively monitoring weather events, climate risks, and asset health by installing washout detectors and laser movement detection systems, using fiber optics to detect slope movements, measuring track stability with radar interferometer, and installing warning systems for extreme weather.	British Columbia
Marine ports, such as Port Saint John, are using real-time weather and wave forecasting tools, including the "SmartAtlantic" inshore weather buoy, to support planning and navigation.	Atlantic
Vessel operators in the Great Lakes-St. Lawrence Seaway System are using Onboard Draft Information systems and other electronic navigation services to support operations in low water conditions, in Arctic waters, vessels are using radar and satellite technology to provide near real-time ice charts, images and forecasts.	Northern Ontario
The Quebec Geomatics Centre and the Ministry of Public Security have implemented an online interactive mapping tool (GéoRISC portal) for the Saguenay-Lac-Saint-Jean region, to allow decision-makers to limit and reduce flooding impacts and ultimately plan for alternative road routes.	Quebec
Operations and maintenance requirements and practices	
To maintain the integrity of winter roads in Northern Canada, operators are spraying roads and bridges and are constructing snow caches at key points along the winter roads, for repair purposes.	Northern Ontario
The City of Toronto is more regularly monitoring and clearing drainage culverts to prevent issues during extreme precipitation events.	Urban
The Quebec Ministry of Transportation has introduced a thermal monitoring program for 13 airport runways in Nunavik. They are built on land sensitive to permafrost thaw.	Quebec
Some jurisdictions are using combination ploughing and salting vehicles to better react to freezing rain conditions.	Urban
Carriers at northern airports have developed portable de-icing mechanisms to more flexibly address aircraft icing requirements.	Northern Prairies
Trucking firms are using technologies to reduce fuel consumption that also enhance climate resilience. Aerodynamic devices (fairings and trailer skirts) can improve the stability of trucks during wind events, and auxiliary power units (APUs) can help truckers respond to increased frequency of cold snaps or heat waves.	Prairies

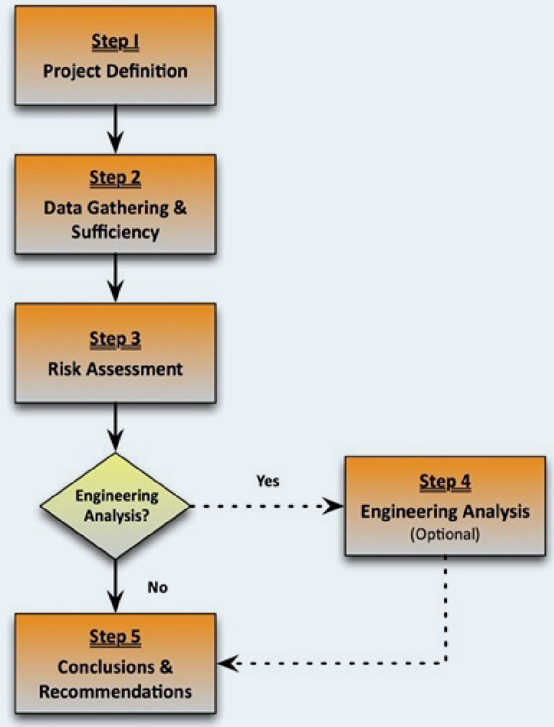
ADAPTING ENGINEERING PRACTICES TO CLIMATE CHANGE

While engineers have long considered climate parameters in engineering design work, this has usually meant looking back at historic trends. Given the current rate of climate change, this is no longer a reliable approach. Provincial Professional Engineering Associations are responding by adding new professional requirements to ensure that potential climate change impacts are taken into account in the design process for the service life expected of the infrastructure. This is a cultural change for agencies responsible for infrastructure, consultants carrying out engineering design work and clients commissioning the work. It is expected that future engineering work related to new infrastructure design and rehabilitation will reflect such action and progress.

The **Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol**, led by Engineers Canada, was developed as a 5-step process to analyze the engineering vulnerability of individual infrastructure systems based on current climate and future climate projections. Since 2012, the Protocol has been applied to a wide variety of infrastructure types, including roads and airports.

For more information, see http://pievc.ca/

Figure 7: Engineers Canada PIEVC Protocol Process. (Source: Engineers Canada)



CONCLUSION

The research conducted for this report suggests that a changing climate and extreme weather are affecting all modes of transportation in every region of Canada, and that many climate risks are increasing. The adaptive efforts being undertaken to date speak to the willingness of Canada's governments, agencies, and private sector to confront the risks to transportation safety, efficiency and reliability posed by a changing climate. At the same time, gaps and barriers remain, including limitations in localized climate projections, and resource and capacity constraints, particularly in Canada's North. Advancements in science and technology, along with training, tools and guidance for practitioners, have the potential to help the sector respond to these challenges. Coordination across jurisdictional boundaries, and with industry and researchers, will be important to advance adaptation solutions and enhance the resilience of the sector in the face of these growing risks.

3 · Northern Territories

CHAPTER 3: NORTHERN TERRITORIES

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[1] The Conference Board of Canada, Ottawa, ON

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KEY FINDINGS

- **The Canadian North has experienced some of the most significant warming on the planet.** From 1948 to 2014, the Arctic Tundra region warmed by 2˚C, while the Arctic Mountains and Fjords region of Nunavut experienced a temperature increase of 1.6˚C. The greatest warming (2.6°C) occurred in the Mackenzie District. These changes have considerable impacts on the people, land, ecosystems, and infrastructure.
- **Permafrost degradation poses both immediate and future risks to northern transportation infrastructure.** Warming temperatures have increased the vulnerability of roads, railways, and airport taxiways and runways to risks associated with ground settlement, slope instability, and buckling. Continued warming will further degrade permafrost, with implications for transportation safety, system efficiency, community services, and maintenance budgets in the North.
- **Changes to the regional climate have reduced the operating windows and load capacities of some winter roads in recent years, in some cases resulting in costly adjustments**. Winter roads serve as a key seasonal component of some territories' transportation infrastructure (particularly in the Northwest Territories) and are critical for community re-supply. While operating windows have always been variable from year to year, recent increases in surface temperature have shortened the operating season for some winter roads. This has resulted in the need for alternative, and often more costly, methods of shipping, such as air transportation.
- **The climatic changes that are opening up northern marine waters to exploration and shipping are also making these activities more difficult.** Increasing temperatures have led to a rapid decrease in sea ice extent, and reduced volumes of multi-year sea ice. While these changes are slowly opening up waterways to new navigational routes, the increased mobility of summer sea ice, as well as increased coastal erosion and storm surge flooding, present ongoing difficulties for shipping, exploration, and associated coastal infrastructure.
- **While many adaptation techniques can be used to maintain roads, rail, and airport taxiways and runways on permafrost rich soil, some can be cost-prohibitive.** Several practices rely on the availability of specialized equipment and materials, which can be expensive to transport to northern locations.

1.0 INTRODUCTION

Canada's North is experiencing some of the most significant warming trends anywhere on the planet (Bush et al., 2014). Changing temperatures, precipitation patterns and storm frequency are affecting northern ecosystems, livelihoods, and infrastructure, including transportation. In addition to withstanding harsh weather conditions, much of Canada's northern infrastructure was designed and built to be operated within a range of site-specific environmental and climate conditions that are changing and will continue to change in coming years (National Round Table on the Environment and the Economy, 2009). In particular, the changing temperatures of the North are affecting the structural integrity of buildings, roads (both all-weather and seasonal), airport runways, rail and marine infrastructure, navigable waterways, and other infrastructure. In the most extreme circumstances, changes have contributed to infrastructure failure (Government of Nunavut et al., 2011). Changing temperatures are also affecting the length of winter road seasons, in some cases resulting in the need for alternative, more costly, shipping methods to reach remote communities (Government of Nunavut et al., 2011). Resulting disruptions to transportation operations can also affect community re-supply and food security. On the water, changing sea ice patterns have affected traditional food harvesting practices and marine shipping (Government of Nunavut et al., 2011).

Trends of warming temperatures and increasingly-severe storm events are projected to continue in the future. Although northern governments and practitioners have begun planning and adapting to climate change, additional practices and resilience-building strategies are needed to ensure the reliability and longevity of transportation infrastructure and systems in northern Canada.

This chapter assesses the many challenges and opportunities for transportation, associated with climate change in Canada's three northern territories – the Yukon, the Northwest Territories, and Nunavut. The chapter provides a regional overview of the territories' distinct geography and transportation networks; discusses observed and projected changes in the northern climate; provides examples of associated impacts on transportation; describes adaptation practices to mitigate these impacts; and identifies gaps in knowledge and research that remain to be addressed regarding future climate risks and opportunities. This synthesis of information aims to enhance understanding of climate risks and adaptation practices within the transportation sector, and inform decision-making.

1.1 REGIONAL OVERVIEW

Canada's North is characterized by its vast size; diverse and rugged landscape; harsh climate; frozen ground (i.e. permafrost); and seasonally frozen waterways and marine waters. The landscape of the North includes long coastlines, Canada's highest mountain range (the Saint Elias in the Yukon), densely forested areas (across much of the Yukon and large parts of the Northwest Territories) and tundra (across all of Nunavut, large parts of the Northwest Territories, and the extreme north of the Yukon).

While the capital cities of the three territories all have populations in excess of 7,000 people, the region's many other communities generally feature small populations situated vast distances from one another, with many only reachable by air or water (see Table 1). These characteristics present challenges for transportation infrastructure and operations – and for economic and social development more broadly – in the North.

Table 1: Territorial North Demographic Overview (2014 population estimates). (Source: Statistics Canada, 2012a, b, c and Statistics Canada 2014).

Indicator	Yukon	Northwest Territories	Nunavut	Total
Population	36,510	43,623	36,585	116,718
Area (km²)	474,713	1,143,793	1,877,788	3,496,294
Population Density/km²	0.1	0.04	0.02	0.03
Number of Communities	19	33	25	77

The economies of the territories are predominantly resource-based – mining and oil and gas production are the region's primary economic drivers. Mining activity and oil production in the Yukon and Northwest Territories are highly dependent upon road transport and systems for supplies and exports. This includes a number of key winter roads that support resource-development projects, particularly in the Northwest Territories (for example, the Tibbitt to Contwoyto Winter Road – see Case study 1). In contrast, economic activities in Nunavut are especially reliant upon sea-based transportation, as there are no roads connecting communities and moving goods by air is costly. In the future, marine transportation is expected to play an increased role in the economies of the territories.

The North also has a vibrant social economy, with a diverse mix of people and cultures. In 2011, 52 per cent of the population of the Northwest Territories, 86 per cent of Nunavut, and 17 per cent of the Yukon identified as Aboriginal (Statistics Canada, 2011). Many traditional ways of life for First Nations (e.g., hunting, fishing, trapping) require ease of movement across land, including accessible routes across snow and ice. Inuit, who have traditionally used sea ice as a "highway" to resources, have been forced to adapt to thinning sea ice. This has required travelling farther distances to hunt and harvest animals that have changed their migratory patterns (Inuit Circumpolar Council, 2008). Northern residents are also affected by high transportation costs, reflected in the prices of food, fuel, and other goods.

2.0 AN INTRODUCTION TO CANADA'S NORTHERN TRANSPORTATION SYSTEM

While territorial transportation networks are similar in some respects, each territory's infrastructure has unique characteristics. For instance, Nunavut has no all-weather roads connecting it to southern Canada, relying instead on air and marine transportation. The Yukon depends primarily on road transportation, and has all-weather roads connecting all communities except for Old Crow. The Northwest Territories, meanwhile, depends on marine, rail, air, and road transportation (Table 2).

The frozen landscape offers opportunities for transportation, providing a seasonal foundation for winter roads. During the winter, sea, river, and lake ice can facilitate the movement of goods and people throughout the territories. However, operating windows for winter roads are limited, with roads typically only in operation from November/December until March/April (Prowse et al., 2009). In addition, permafrost conditions affect the stability of all-season transportation infrastructure, including roads and airport runways.

During the summer, navigable waters are used for shipping purposes, providing community resupply to remote areas. The air sector plays a significant role in all three territories and serves as the year-round link between northern communities and southern Canada for essential medical and evacuation services.

In light of the risks to northern transportation systems posed by a changing climate (discussed in detail in subsequent sections), the need for adaptation related to transportation has been acknowledged by both federal and territorial governments. The Government of the Northwest Territories commissioned the development of a Climate Change Adaptation Plan for the Department of Transportation in 2013 (Deton'Cho-Stantec, 2013). Nunavut established the Nunavut Climate Change Centre, released a report on climate change impacts and adaptation, and collaborated with the Canadian Institute of Planners on an "adaptation planning toolkit" in 2011 (Government of Nunavut, 2011; Bowron and Davidson, 2011). The Nunavut government also produced a report on engineering challenges for coastal infrastructure, including docks, in relation to the impacts of climate change (Journeaux Assoc., 2012). Adaptation work is ongoing in the Yukon, particularly at Yukon College and through the Yukon Climate Change Secretariat (Northern Climate ExChange, 2014a and 2014b). Several of these efforts have been undertaken in collaboration with federal departments, including Transport Canada and Natural Resources Canada.

2.1 SYSTEM OVERVIEW

Figure 1 and Table 2 present an overview of transportation routes and infrastructure in Canada's North. The following sections discuss the regional significance of each of the major modes of transportation – road transport, aviation, marine transport, and rail – in greater depth.

Figure 1: Map of principle transportation infrastructure in northern Canada. Note that the National Road Network includes winter roads.

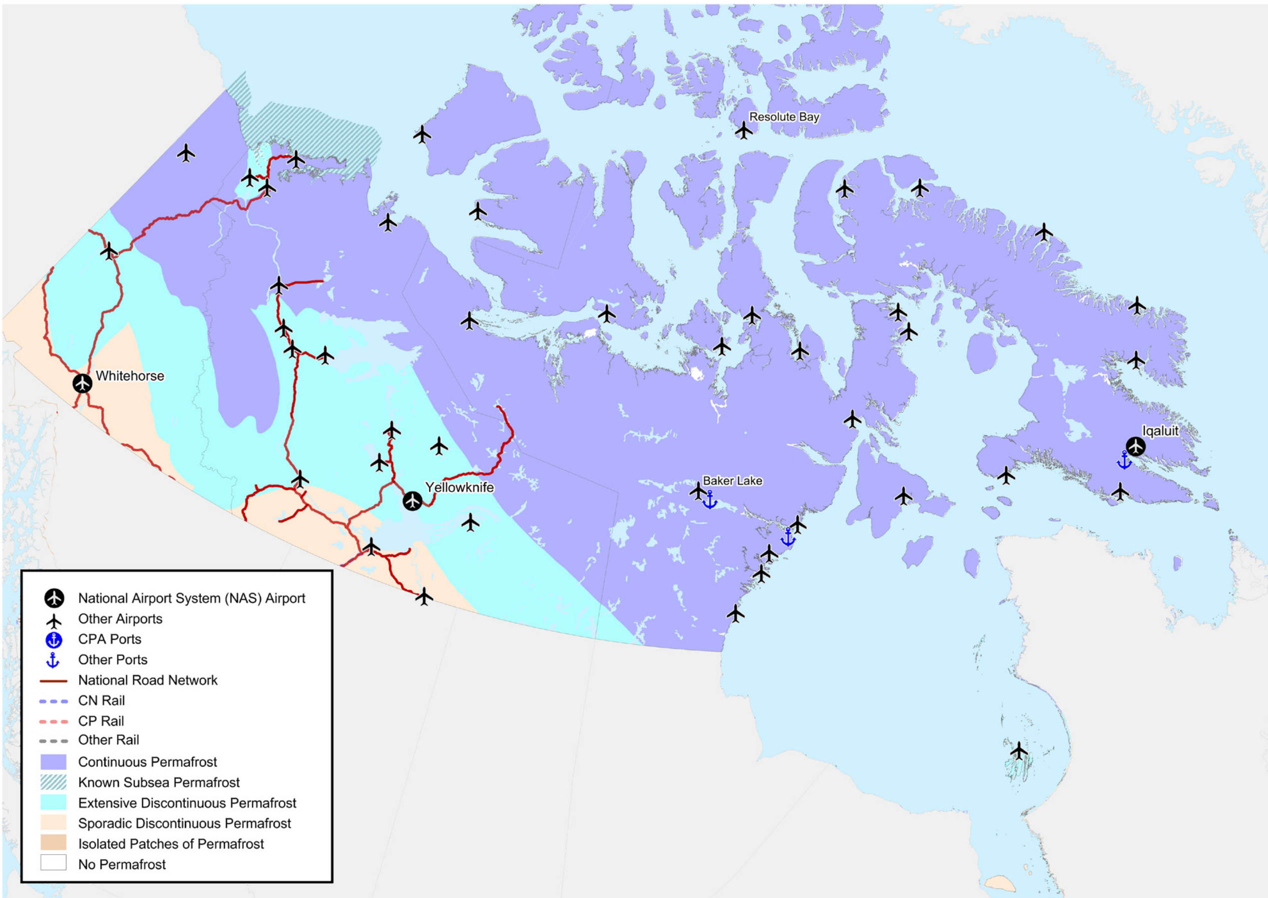


Table 2: Transportation networks in the territories at a glance.

	Yukon	Northwest Territories	Nunavut
Highways	• 4,800 km of all-weather roads - 1,069 km of National Highway Core Routes - 5% paved - 40% chip-sealed - Remainder is gravel • 129 bridges • With the exception of Old Crow, each Yukon community is connected to the highway	• 2,200 km of all-weather roads - 576 km of National Highway Core Routes - 45% paved/chip-sealed - 27% gravel • Over 300 bridges • 4 ferry crossings (Highways 1 and 8) with operations from May/June to October/December • 1,625 km of publicly constructed winter road • Privately constructed / maintained winter roads, including the 570-km Tibbitt to Contwoyto winter road, used by both industry and the public	• No roads connecting communities • Each community has a series of access trails that lead to fishing, hunting and camping areas • No winter road system to date

	Yukon	Northwest Territories	Nunavut
Airports	• 4 airports and 25 aerodromes[2] - 1 international hub (Whitehorse) - 2 airports (Whitehorse and Watson Lake) have paved runways; all others have gravel airstrips	• 27 airports - The hub (Yellowknife), connects to the provinces as well as communities within the Northwest Territories - 2 regional hubs (Norman Wells and Inuvik) - 24 community airports - 6 airports with paved runways; all others are gravel	• 25 airports - 2 airports (Iqaluit International and Rankin Inlet) with paved runways; all others are gravel
Marine	• Links to the marine transportation network via Alaska through ports such as Skagway, AK and Haines, YT	• Privately operated resupply tugboats and barges serving industry, residents, and delivering fuel for electricity generation • Privately operated supply barges to communities • Federal installations exploration camps and Arctic communities • River transportation (including the Mackenzie River) is especially important for community resupply and delivering fuel to industry and residents	• Pangnirtung has a small craft harbour which includes a fixed wharf, breakwater and sea lift ramp • No other community has harbour facilities • Marine access plays a vital role for community resupply; however few communities have docking facilities
Rail	• Limited rail in the Yukon for tourism purposes	• The Mackenzie Northern Railway is used for the transport of bulk commodities from Alberta into Hay River and Enterprise	• Currently no railways in Nunavut

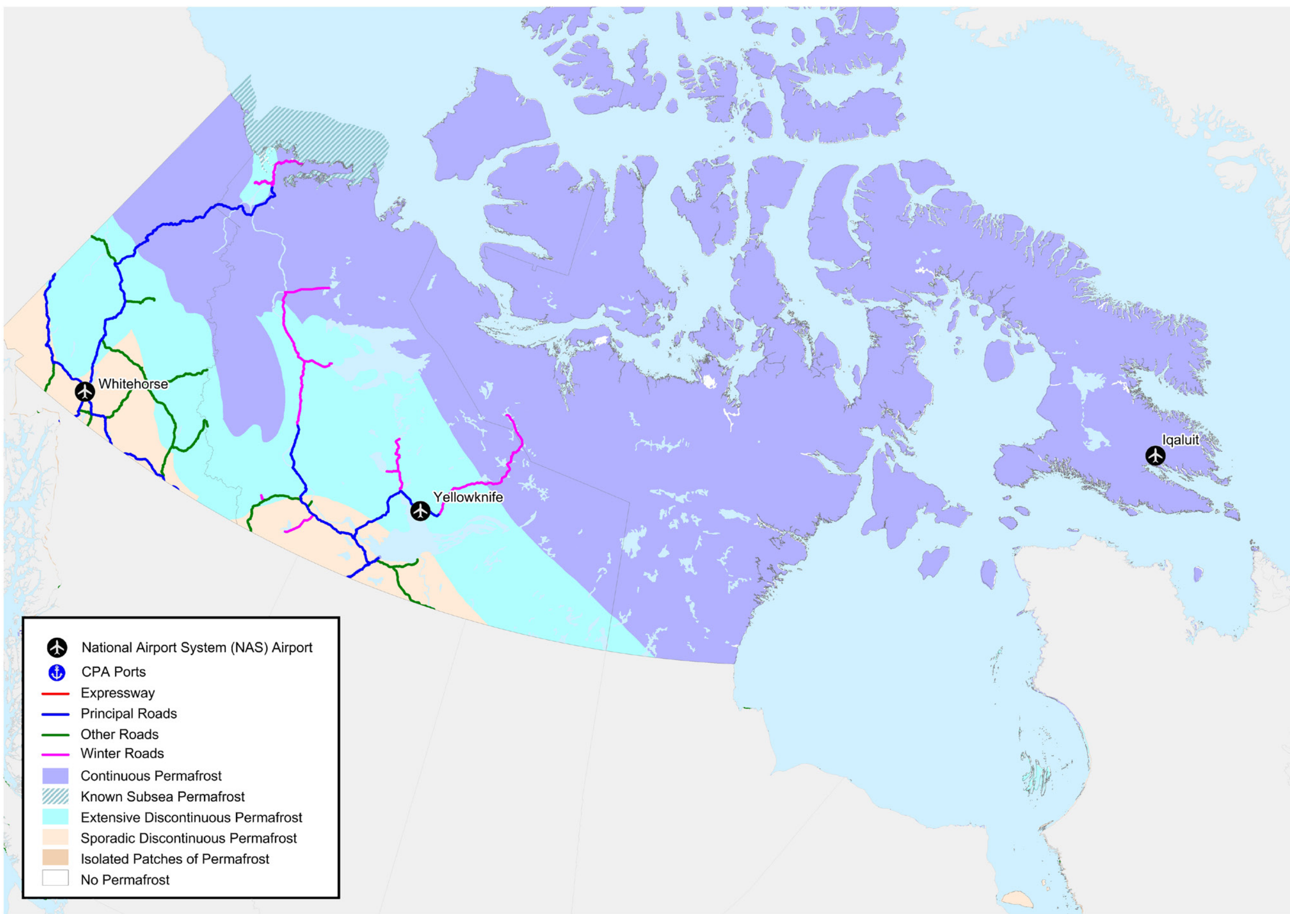
2.2 ROAD TRANSPORTATION

In the Yukon, the land-based transportation network is relatively well-developed, with roads connecting all communities but one (Old Crow, the territory's most northerly community, is linked to the continental mainland only seasonally via winter roads extending to Inuvik and Alaska). In contrast, few communities in the Northwest Territories and no communities in Nunavut are connected to southern Canada via the national highway system (Prolog Canada Inc., 2011). The all-weather road system in the Northwest Territories is being expanded through construction of a road from Tuktoyaktuk to Inuvik (expected to be completed in 2018) (Government of Northwest Territories, 2015a). In addition, ferry services have been added on the Peel and Mackenzie Rivers, and there are plans to extend the all-weather Mackenzie Highway further north. This highway extension would reduce the need for winter road use and yield potential economic benefits for communities along the route from Wrigley to Tuktoyaktuk (Yukon Government et al, 2008).

2 Aerodrome: Any area of land, water (including the frozen surface thereof) or other supporting surface used or designed, prepared, equipped or set apart for use either in whole or in part for the arrival, departure, movement or servicing of aircraft and includes any buildings, installations and equipment situated thereon or associated therewith. (Transport Canada, 2014)

As discussed, winter roads constitute an important component of northern Canada's surface transportation network. Goods transported include bulk fuel, dry goods, building material and other items with a maximum truck load capacity of 64,000 kg (Federal, Provincial, and Territorial Sub-Working Group on Northern Transportation, 2015). In the Yukon, winter roads facilitate community transportation (Deton'Cho-Stantec, 2013). There is no winter road system in Nunavut; however, the Government of Nunavut is assessing the feasibility of developing a seasonal network connecting the Kivalliq region with northern Manitoba (Brownie, 2013). Winter roads are much less costly than all-weather roads, and have a much smaller environmental footprint (Transportation Association of Canada, 2010). While a 9m-wide all-weather road in the Northwest Territories can range from CAD$1.2 million to CAD$1.5 million per km (with maintenance costs up to CAD$15,000/km/year), winter roads range in cost from CAD$10,000 to CAD$20,000/km/season to open and operate (Transportation Association of Canada, 2010).

Figure 2: Road network in the Yukon and Northwest Territories.



2.3 AVIATION

For communities not connected by all-weather or winter roads, air transportation is vital. This is especially true in Nunavut and the Northwest Territories, where aviation ensures community resupply and transportation year-round. To illustrate its predominance, consider that more than 110,000 people departed from and disembarked at the Iqaluit airport in 2006, despite a population of approximately 6,000 at the time (Dunlavy et al., 2009). While Yukon communities are not as heavily dependent on air travel due to the territory's extensive road network, aviation remains important for isolated communities like Old Crow.

While some runways in the territories are paved, the vast majority are gravel. Paved and gravel runways have different sensitivities to climate (in particular to changes in ground conditions), and therefore require different adaptation methods. However, while gravel runways may be easier to maintain in a northern context, no new-generation jet aircraft are certified to operate on non-paved surfaces (Parliament of Canada, 2011). The Boeing 737-200, which has not been manufactured since the 1980s, is the most modern gravel-kitted aircraft. However, this model has higher fuel consumption and upkeep costs compared to more modern aircraft (Parliament of Canada, 2011).

2.4 MARINE TRANSPORTATION

Marine transportation is also important for community resupply (e.g., the transportation of food and fuel) during shipping months in the Northwest Territories and Nunavut. Despite its coastline along the Beaufort Sea, the Yukon has no marine-based facilities, although there is docking infrastructure along the Yukon River. While marine shipping is more cost-effective than air shipping in Nunavut, it is often hampered by a lack of port infrastructure and difficult conditions on the water. Cambridge Bay has basic facilities, and only Pangnirtung has a harbour facility. Inland marine transportation from Hudson Bay to Baker Lake (via the Chesterfield Narrows) is used to deliver fuel and construction supplies by barge and tanker to support the construction and operation of the Meadowbank gold mine (Transportation Safety Board of Canada, 2012). There are also plans to expand marine usage in some places. At Pond Inlet, a new marine and small craft harbour is planned; this would increase the community's capacity for resupply of food, fuel and other goods (Government of Canada, 2015). Additionally, the Iqaluit Marine Infrastructure Project – involving the construction of a port and sea lift facility – aims to reduce offloading times and improve worker safety (Government of Nunavut, 2015).

The Northwest Territories has an extensive network of river transportation vessels and facilities used for community resupply. The Mackenzie River acts as an important cargo shipment route for transporting goods to communities along the river, the Mackenzie Delta, the coast of the Beaufort Sea and the interior of the Canadian Arctic Archipelago (Deton'Cho-Stantec, 2013). Additionally, some suggest that marine facilities in Tuktoyaktuk harbour once used to support oil and gas activities in the Beaufort Sea could be revamped to support offshore activity and search and rescue operations (Matthews, 2014). However, the port is not suitable for larger vessels and currently features a shallow 32-km channel approach with sections less than 4m deep (Prolog Canada Inc, 2011).

2.5 RAIL TRANSPORTATION

Rail infrastructure is limited in the territories, but provides important services in some locations. For example, Canadian National (CN) Railway runs one return bulk commodity train daily to Enterprise and Hay River, Northwest Territories, that supplies the community and mining industry (Yukon Government et al, 2008). The line is one of the most costly routes in CN's network due to the challenging area of service; for instance, the rail bed is constructed on permafrost, which limits train speed (Government of Northwest Territories, 2015a). Maintaining this service is important, however – over half of all bulk commodities entering the territory do so by rail (e.g., petroleum, agriculture and forest products) (Government of Northwest Territories, 2011).

The only rail line operating in the Yukon is the White Pass and Yukon Route, which operates as a tourist train from Carcross, Yukon to Skagway, Alaska (White Pass and Yukon Route, 2015). However, this may change: a study has been completed investigating the feasibility of a rail link from Alaska and the Yukon to the North American rail grid. This route would provide an alternative North American gateway to the Pacific Rim via ports in northern British Columbia and Alaska (Yukon Government et al, 2008).

3.0 CLIMATE

Canada's northern territories are characterized by long cold winters interrupted by short, relatively cool, summers. Precipitation is light, particularly in the western and northern parts of the region, and occurs predominantly in the summer months. There is great regional variability in both seasonal temperatures and precipitation. For example, average winter temperatures in the northern part of the region are around -37˚C, but only -18˚C in the south (Environment Canada, 2015). Average summer temperatures range from 16˚C in the south to 6˚C in the north. Variability among seasons, years, and decades is high.

A critical component of the northern climate system is the cryosphere – terrestrial, freshwater, and marine areas that are seasonally or permanently frozen. This includes snow, glaciers, and permafrost, as well as lake, river and sea ice. Many of the most dramatic climate change impacts observed in Canada's North relate to changes in the cryosphere (Derksen et al, 2012). A final element of the northern climate system is the marine climate. While changes in ocean temperature, salinity, and other parameters have important implications for northern ecosystems and traditional ways of life, this chapter only considers changes in sea level as it affects coastal transportation infrastructure.

3.1 TRENDS AND PROJECTIONS

3.1.1 ATMOSPHERE

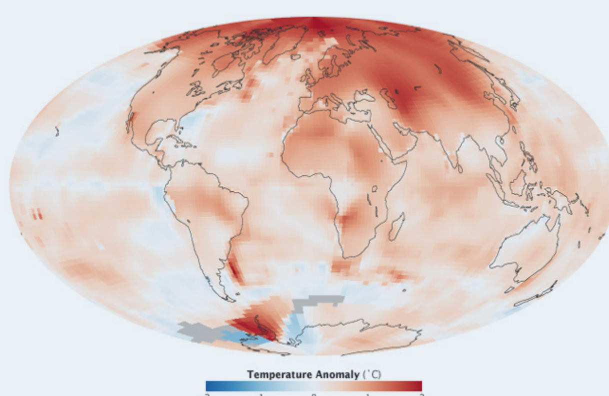
Arctic regions have warmed, and will continue to warm, more rapidly than most regions of the world, due in part to the phenomenon known as Arctic amplification (see textbox). Canada's North has already experienced some of the most significant surface air temperature warming observed anywhere on the planet (Bush, et al., 2014). The greatest observed warming, 2.6˚C for the period 1948-2014, has occurred in the Northwest Territories' Mackenzie District (Environment Canada, 2015). Over the same period, the warming trend in Canada was 1.6˚C, and about 0.8˚C globally. Warming over the rest of northern Canada was equal to or greater than warming observed over the country as a whole for the period 1948-2014, with warming of 2˚C observed in the Arctic Tundra region, and 1.6˚C for the Arctic Mountains and Fjords region of Nunavut.

Projections suggest that warming of the North will continue to be greater than in Canada as a whole, with the greatest warming occurring in winter and fall (Bush et al., 2014). In climate change models, the magnitude of warming for the latter part of this century is strongly dependent upon the level of global greenhouse gas emissions. Under a high-emissions scenario, winter warming in excess of 10˚C is projected for large areas of the North.   Even under a low emissions scenario, average winter temperatures will increase by more than 5˚C.

WHAT IS ARCTIC AMPLIFICATION?

Arctic amplification refers to the faster rate of warming that characterizes Arctic regions relative to the rest of the world (Figure 3). While many factors contribute to this phenomenon, one key factor is the increased surface absorption of heat associated with reductions in snow and sea ice cover. Snow and ice are highly reflective, whereas the darker surfaces of open water and tundra absorb heat, causing greater warming (National Aeronautics and Space Administration, 2013).

Figure 3: Global temperature anomalies for 2000 to 2009, showing how much warmer (red) or colder (blue) a region is compared to the norm for that region from 1951 to 1980. While average global temperatures from 2000-2009 were about 0.6°C higher than they were from 1951–1980, the Arctic warmed by about 2°C. (Source: Courtesy NASA/JPL-Caltech)



All regions of northern Canada have also shown increases in precipitation since 1948, with very high variability from one year to the next (Prowse et al., 2009). While the region is dominated by cold air masses in winter, increased variability in the jetstream in recent years (Francis and Vavrus, 2012) has resulted in more winter warm-air advection events in the North (winds blowing from warmer regions) (Wang, 2006). This can bring freezing rain, fog and melt events, which cause problems for transportation systems. Climate projections indicate that precipitation will continue to increase under all scenarios, with the greatest increases in fall and winter. Winter precipitation increases greater than 25 percent are projected for parts of the eastern and central Arctic by the year 2050 (Bush et al., 2014).

There is strong evidence that the frequency and intensity of storms in the Arctic is increasing (Manson and Solomon, 2007). Increasingly-large areas of open water result in more intense cyclonic storms – these storms will grow larger and stronger as sea-ice extent is projected to decrease even further (Simmonds and Keay, 2009). Storms are most common in the eastern Arctic, associated with the Baffin Bay storm track. There are many recent examples of severe wind events, including a 2006 event in Pangnirtung, Nunavut, where winds reaching 125 km/hr destroyed a building and broke windows (Hanesiak et al., 2010). During a similar 2007 event in Iqaluit, Nunavut, winds reaching up to 140 km/hr tore sections off the roofs of multiple buildings (Hanesiak et al., 2010). Storm surges, where water levels exceed predicted tide levels due to atmospheric pressure and winds associated with storms, are of particular concern along the Beaufort Sea coast due to its shallow depth. Several sites in that region have recorded storm surges in excess of 2 m (Forbes and Frobel, 1985), with impacts extending 30 km inland on the Mackenzie Delta (Kokelj, et al., 2012). When storm surges occur during periods of full ice cover, "pressure ridges" can result that alter the sea floor near the shore, potentially affecting access to coastal facilities.

3.1.2 CRYOSPHERE

Dramatic changes have been observed in all elements of the cryosphere, and the rate of change has been accelerating in recent years (Derksen et al., 2012). These changes include decreases in the extent and duration of snow cover over the past 40 years, and a strong shift towards negative mass balance (loss of ice volume) in Arctic glaciers and ice caps since 2005 (Derksen et al., 2012). Of particular relevance to northern transportation are changes in sea ice, permafrost, and river and lake ice cover.

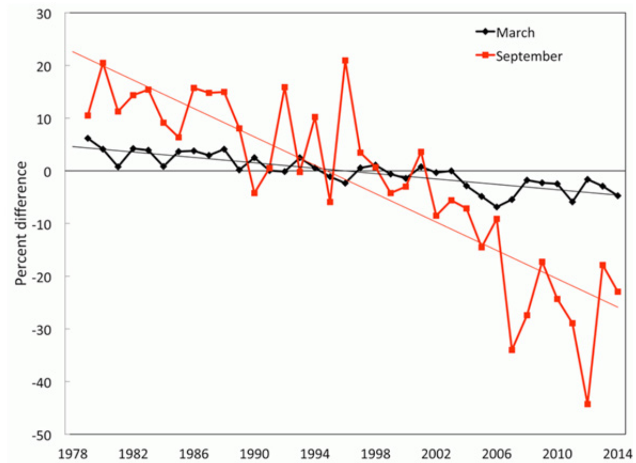
Sea ice is one of the most defining features of Canada's North (Ford et al., 2016). In winter, when ice cover is essentially complete, the coast is protected from wave action, and ice permits transportation between communities and access to hunting and fishing areas. When ice is in motion, wind and currents can cause ice flows to collide and form pressure ridges, making travel both through the water and over the ice more difficult. Thick multi-year sea ice associated with the break-up of ice islands and icebergs generated by calving glaciers also present significant hazards for marine shipping (Prowse, et al, 2009).

For the Arctic as a whole, the average extent of sea ice in the month of September is decreasing at a rate of 13.3 percent per decade, while March extent is decreasing at a rate of 2.6 percent per decade (National Snow and Ice Data Centre, 2016) (Figures 4a, b, c). In the Canadian Arctic, the rate of loss ranges from 2.9 percent per decade in the Canadian Arctic Archipelago (CAA) (although areas within the CAA have much higher rates) to 10.4 percent per decade in Hudson Bay (Tivy, et al., 2011). This decline in sea-ice cover has resulted in a lengthening of the open-water season by an average of five days per decade Arctic-wide since 1979 (Stroeve, et al., 2014), and by 3.2–12 days per decade in the Canadian North. For example, in Resolute Bay, Nunavut, the melt season has increased by close to 30 days over a 30-year period, driven primarily by a delay in freeze-up (St-Hilaire-Gravel et al., 2011). The decrease in the extent of sea ice means that larger and more powerful waves are reaching the coast (Overeem et al, 2011). This in turn, leads to increased erosion and flooding (Solomon et al., 1994). The greatest increase in fetch (length of open water) generally occurs in September, which is often also the stormiest period of the year (Atkinson, 2005).

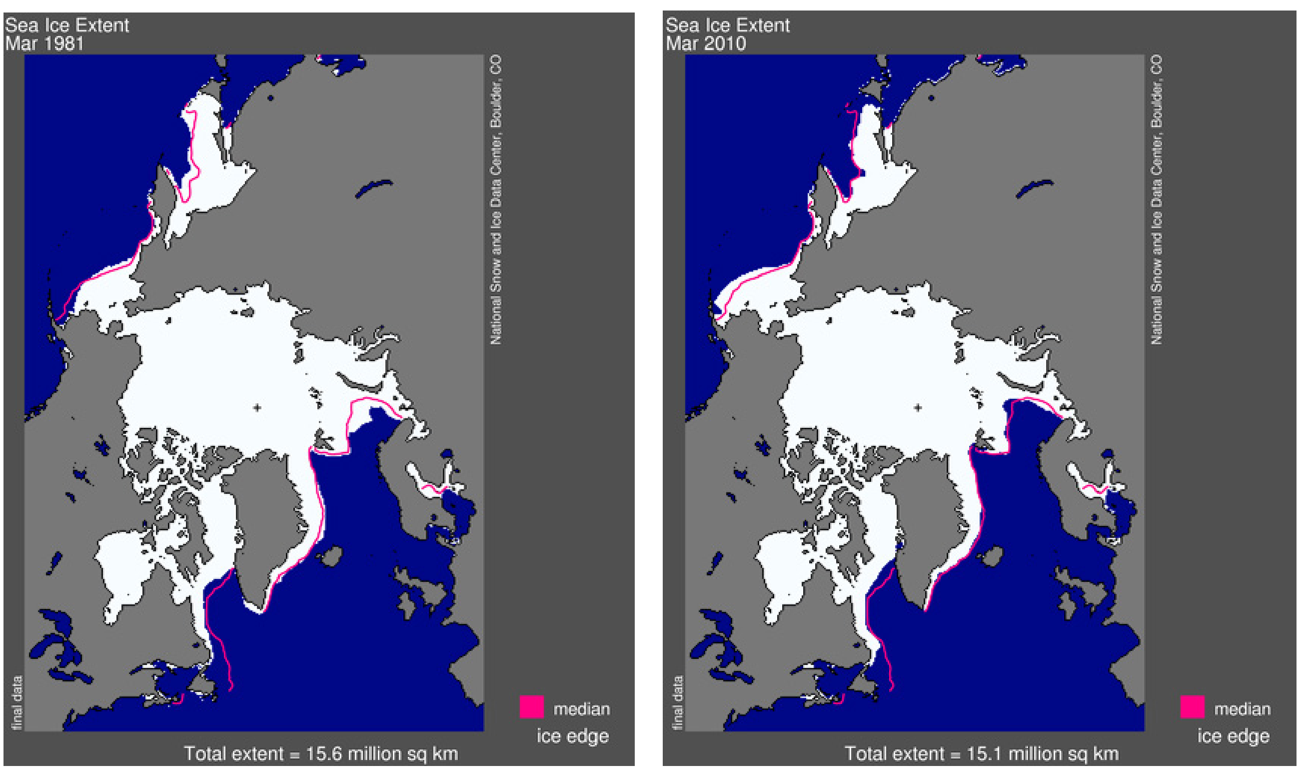
These trends in sea-ice cover are expected to continue or accelerate (Vaughn et al., 2013), with some models projecting almost complete loss of summer ice cover before mid-century (Wang and Overland, 2012). Arctic sea ice is also thinning, with the average spring ice thickness projected to decrease from 2.4 m in 2008 (Kwok et al., 2009) to 1.4 m by 2050 (Stroeve et al., 2012).

Figures 4a, b, c: Changes in Arctic sea ice extent since 1981. (Source: Courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder)

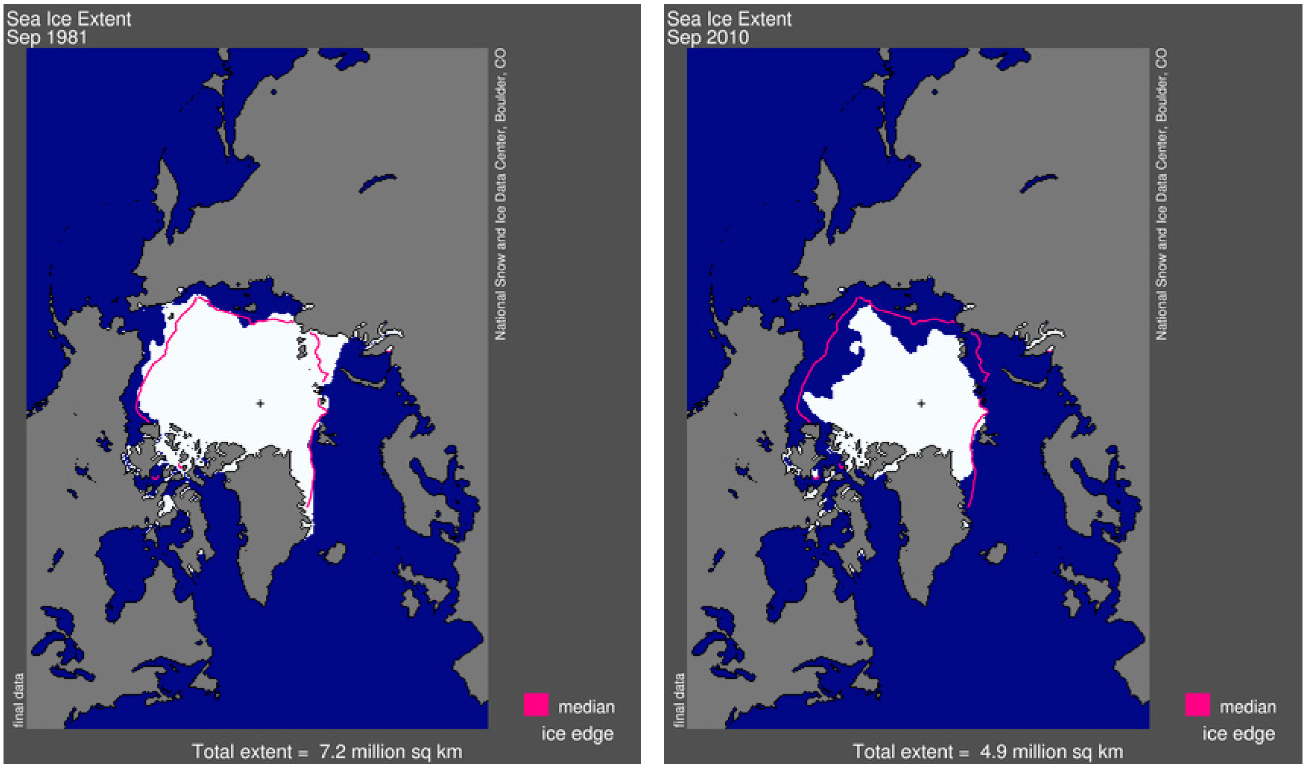
4a – Annual sea-ice extent anomalies (relative to the mean values for the period 1981–2010) for the months of maximum and minimum ice extent (March and September, respectively). (Perovich et al., 2014)



4b – Comparison of mean monthly sea ice extent for March 1981 and March 2010, with magenta line depicting median May ice extent for the period of record. (National Snow and Ice Data Center, 2016)



4c - Comparison of mean monthly sea ice extent for to September 1981 and September 2010, with magenta line depicting median September ice extent for the period of record (National Snow and Ice Data Center, 2016). The decreases in minimum ice extent have been much more dramatic than have changes in maximum ice extent.



Permafrost – which is permanently frozen ground – underlies virtually all of Canada's northern territories. It can be continuous or discontinuous, or occur only in patches (Smith and Burgess, 2004). Permafrost can be up to several hundred metres thick, but may be only tens of metres thick or less in more southerly parts of the permafrost zone. Above the permafrost, a surface layer (known as the active layer) thaws in summer and refreezes in winter. The active layer can range from tens of centimetres to several metres in thickness. Climate (including air temperature and snow cover) is the main factor controlling the occurrence and thermal state of permafrost. Changes in climate can result in permafrost warming and thaw. Warming of permafrost reduces the structural integrity of infrastructure that relies on permafrost for a stable foundation, while thawing of ice-rich permafrost leads to surface subsidence (sinking), hydrological changes and slope instability. This presents risks to infrastructure, roads, airstrips, and railways.

A number of comprehensive overviews of the state of permafrost in Canada (Burn and Kokelji, 2009) indicate that, with few exceptions, permafrost temperatures are increasing. Generally, colder permafrost situated further north has seen greater increases in temperature than warmer permafrost. Multi-decadal trends show warming of ground temperatures of between 0.2˚C per decade in the southern and central Mackenzie Valley to 1.2˚C per decade in the eastern Arctic (Figure 5). These rates appear to be increasing, with data for the period 2008 to 2013 showing average warming of 1.5˚C per decade for 10 sites spanning a range of Arctic environments (Smith et al., 2013). Ground warming is also associated with an increase in the thickness of the seasonal active layer.

These trends are projected to continue as the climate continues to warm (Woo et al., 2007). Regions that experience the greatest thermal responses, however, are not necessarily the ones that exhibit the greatest physical impacts (Smith and Burgess, 2004). For example, where there is a large increase in ground temperature but very low ground ice content, the physical impacts of permafrost warming will be minimal.

Figure 5: Mean annual ground temperature (MAGT) across northern Canada recorded during the International Polar Year (2007-09). B and C show permafrost temperature standardized anomaly time series (relative to 1988-2007 mean) for a site near Norman Wells (12 m depth) and at Alert (15 m depth). (Source: Derksen et al., 2012)

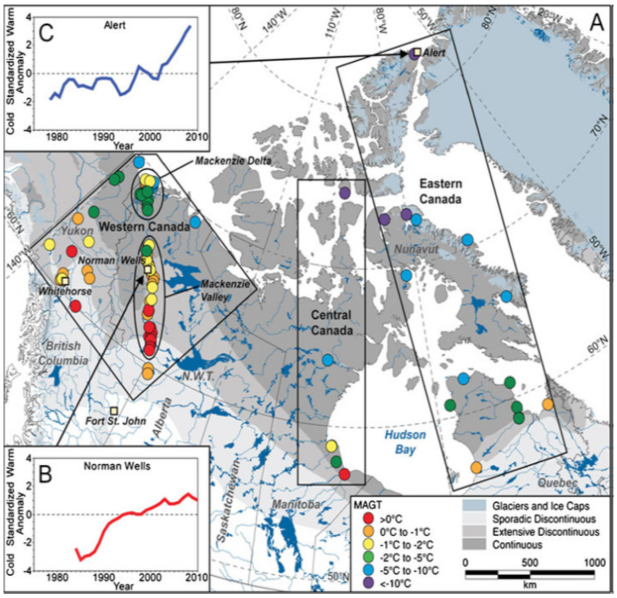
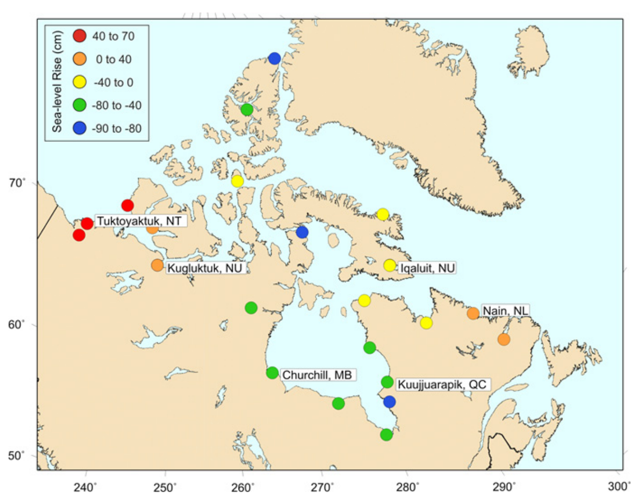


Figure 6: Projected median relative sea-level change in 2100 for a high greenhouse gas emissions scenario (RCP8.5; after James et al., 2014). The scenarios and methods used are described in Atkinson et al., 2016. (Source: Natural Resources Canada)



Air temperature also strongly influences the freeze-up and break-up dates of river and lake ice, while changes in both air temperature and snow cover affect ice thickness (Brown and Duguay, 2010). Duration and thickness of ice cover are critical for the sustainability of many winter roads in Canada's northern territories. Delayed freeze-up, and earlier break-up dates observed in recent years are projected to continue, with simulations suggesting that by mid-century freeze-up will occur about 15 days later than it has historically, and that break-up will occur 5 to 25 days earlier. For the same period, maximum ice thicknesses are projected to decrease by 20 to 30 cm (Brown and Duguay, 2010).

3.1.3 SEA LEVEL

Sea level changes in Canada's northern territories are dominated by vertical land motion that has been ongoing since the last glaciation, when the land beneath ice sheets was depressed hundreds of metres, and has slowly been rebounding back over thousands of years (Atkinson et al., 2016). This phenomenon, known as glacial isostatic adjustment, results in observed sea level falling across most of the Canadian Arctic, despite the fact that global mean sea level has risen. An important exception is the Mackenzie Delta/Beaufort region of the western Arctic that lay near the margin of the last ice sheet and is experiencing sea level rise as a result. Tide-gauge records covering the past 50 years indicate that sea level has risen 2.4 mm/year at Tuktoyaktuk, NT, but fallen by 1.5 mm/year at Alert, Nunavut (Ford et al, 2016).

Future patterns of sea level change will be similar to historic patterns, with the magnitude of change influenced by global greenhouse gas emissions and associated increases in mean global sea level. Where the land is currently rising rapidly, future sea level is projected to continue to fall, even under a high greenhouse-gas emissions scenario, and some locations could experience more than 80 cm of sea-level fall by 2100 (Figure 6). Where the land is sinking slowly, including the Mackenzie Delta/Beaufort region, sea level is projected to rise more than 40 cm by 2100. While not all of this change is due to a changing climate, adaptation will still be required.

An important consequence of sea-level rise is the associated increase in extreme water-level events. For example, at Tuktoyaktuk, sea-level rise is projected to increase the frequency of an event that has historically occurred once every 25 years to once every 4 years by 2100. In other words, the flooding level associated with a one-in ten year event at Tuktoyaktuk is expected to increase from 1.1 m at present to 2.1 m by 2100 (Lamoureux et al., 2015).

While changes in sea level will have an impact on transportation and associated coastal infrastructure in the long term, particularly in the Mackenzie Delta/Beaufort region, near-term changes in sea-ice extent and duration will produce far more significant impacts on coastal erosion and flooding (Ford et al., 2016). Coastal erosion and related damage to infrastructure is already a significant issue for many communities in the western Arctic. For instance, Tuktoyaktuk has experienced such significant coastal erosion that several buildings, including the community school and police station, have been moved to ensure the safety of residents (Government of Nunavut et al., 2011).

4.0 ROAD IMPACTS AND ADAPTATION

4.1 CLIMATE IMPACTS ON ROAD TRANSPORTATION

As discussed, roads are critical to the socioeconomic functioning of many northern communities. This section summarizes expected impacts on roads associated with different climatic factors.

4.1.1 ALL-SEASON ROADS

Warming temperatures in northern Canada have significant impacts on roads, especially those constructed on permafrost (Northern Climate ExChange, 2014b). Permafrost conditions are particularly challenging for engineers working at the southern limits of the North, where ground temperatures fluctuate between -1°C and 0°C. Warming and thawing of ice-rich permafrost can lead to ground settlement, slope instability, drainage issues, and road cracking (see Figure 7) (Montufar et al., 2011). For instance, Highway 3 in the Northwest Territories was designed to preserve permafrost, but the high volume of melt water due to warming temperatures was not taken into account and infrastructure failed as a result (Northern Climate ExChange, 2014b).

Figure 7: Differential settlement associated with permafrost thaw along an abandoned section of Northwest Territories Highway 4, east of Yellowknife. (Source: Natural Resources Canada)

Extreme precipitation events have also affected roads and bridges. For example, heavy rains and flash flooding in Pangnirtung, Nunavut washed out a major community bridge, stranded 200 residents, and blocked access to important municipal services (CBC News, 2008). Field investigation determined that heavy rains, warmer-than usual-temperatures, the presence of ice-rich materials, and frost cracking were the main contributing factors (Hsieh et al., 2011).

4.1.2 WINTER ROADS

Higher temperatures also have a negative impact on winter roads, which may be constructed overland, across lake and river ice, or (in a few cases) sea ice fastened to the shore. While operating windows have always varied by location and year, recent increases in surface air temperature and decreases in snow cover have reduced operating season length and maximum load capacity in many locations (Furgal and Prowse, 2008). This resulted in a costly adjustment in 2006, when approximately 1,200 loads had to be transported by air during the summer and fall following a shortened winter-road season on the Tibbitt to Contwoyto Winter Road (Andrey et al., 2014).

Drainage issues can also intensify in periods of extreme weather, as water flow can reduce the integrity of winter roads, bridges at stream crossings, and culverts. For example, sections of the Mackenzie Valley and Tlicho Winter Roads have experienced flooding and closure in recent years, and the Tlicho Winter Road has experienced shut downs in sections due to flooding (Deton'Cho-Stantec, 2013).

4.2 FUTURE RISKS

4.2.1 ALL-WEATHER ROADS

A significant threat to the integrity of roads throughout most of the territories is the continued degradation of ice-rich permafrost. This is expected to continue to cause issues related to ground settlement and road-embankment subsidence – over the long term, permafrost degradation may contribute to the failure of highway side slopes, increased sloughing (referring to the movement of supporting material downhill and away from the roadway) (Alberta Transportation, 2003), as well as the sinking and cracking of road shoulders (Deton'Cho-Stantec, 2013).

More frequent extreme rainfall events would exacerbate the potential for flooding in some areas, leading to road and bridge washouts, reduced friction, and drainage issues related to inadequate culvert sizing. High-volume snowmelt may also result in flooding and increase pore water pressure and erosion, damaging permafrost (IMG-Golder Corporation Environmental Consulting, 2012). This will have implications for roads, bridges at stream crossings, and slope stability. Territorial governments are aware of these risks and have been taking steps to increase the structural integrity of the ground underlying transportation infrastructure (discussed further in Section 4.3). In addition, snowfall and winter storm events limit visibility for drivers, and may result in road closures.

4.2.2 WINTER ROADS

As the climate warms, winter roads in the Canadian North, both public and private, are at risk due to shortened operating seasons and increased costs. Thinner lake, river, and marine ice will have a negative impact on the seasonal duration and stability of winter roads (Bush, et al., 2014), while changing permafrost conditions could impact the viability and structural integrity of some routes (McGregor et al., 2008).

The trend towards shorter operational seasons is already evident. For example, the average opening date for light traffic on the Mackenzie River Ice Bridge Crossing has been delayed, on average, by more than 3 weeks since 1996 (Frugal and Prowse, 2008). In the future, some winter routes may become impractical, although timing and locations have yet to be determined. Alternative transportation routes or modes will need to be considered in advance of reaching such thresholds (Frugal and Prowse, 2008) (see Case study 1).

CASE STUDY 1

CASE STUDY 1: IMPLICATIONS OF A CHANGING CLIMATE FOR THE TIBBITT TO CONTWOYTO WINTER ROAD

The Tibbitt to Contwoyto Winter Road (TCWR; Figure 8) is a 570-km private industrial road (also used by the public) in the Northwest Territories and Nunavut. It provides access and supplies to three active diamond mines and other mining locations. The majority of the road is built over frozen lakes, and both the construction and operation of the road are sensitive to climate variations. Thus, winter warming trends have been identified as a concern for the longevity of the road.

TCWR Facts:

- The TCWR is the busiest heavy-haul winter road in the world, moving a record 10,922 loads (330,002 tonnes) in 2007. It provides access to a region served by no other highways.
- The minimum ice thickness required for very light loads is 70 cm, while 107 cm is required for maximum loading (42 tonnes). Ground-penetrating radar is used to measure ice thickness.
- Construction of the road takes approximately 5 to 6 weeks prior to opening each year.
- The TCWR is typically operational for 8 to 10 weeks, starting between January 26 and February 11 and ending between March 21 and April 16.

Climate trends: Analysis of regional climate data demonstrates that the TCWR's operating season length correlates with temperature and related variables, including freezing-degree days, melting-degree days, and ice thickness – of these, the strongest indicator of a longer season is the accumulation of freezing-degree days. Winter temperatures in the region have increased significantly over recent decades (Figure 9); correspondingly, freezing-degree days and observed annual maximum ice thickness have both decreased, while melting-degree days have increased.

Figure 8: Map of the TCWR's route through the Northwest Territories and Nunavut. (Source: Tibbitt to Contwoyto Winter Road Joint Venture)

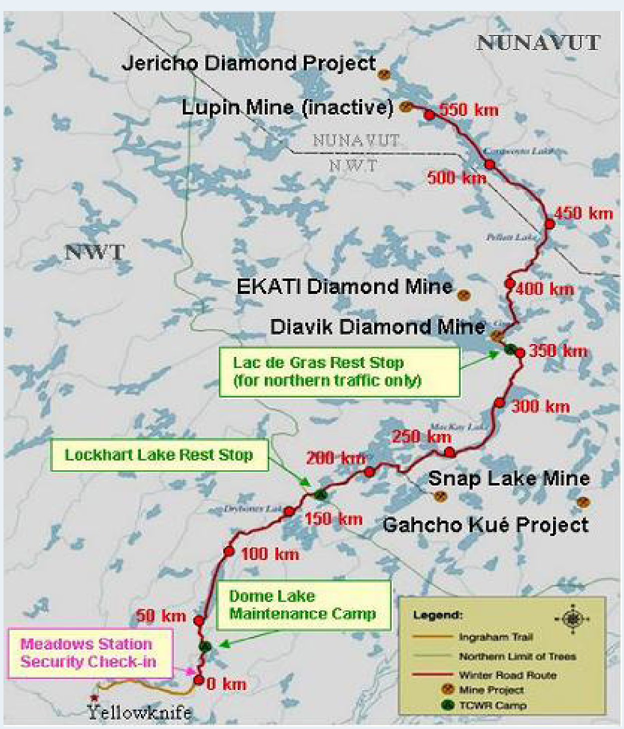
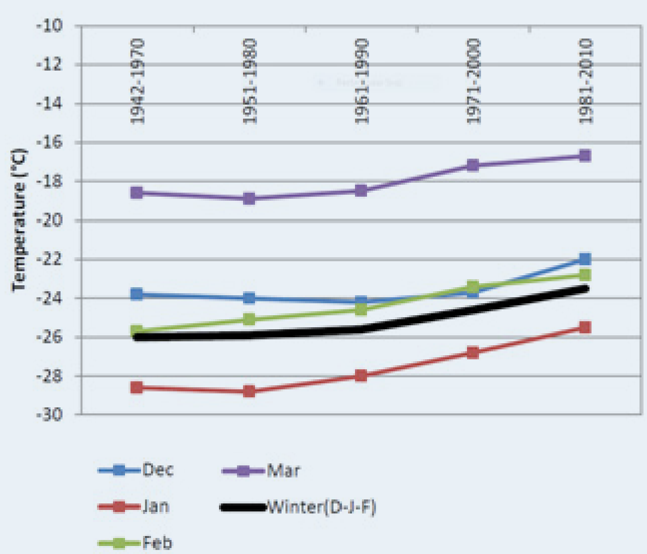


Figure 9: Historical average temperatures observed in Yellowknife for five previous climate normal periods. (Source: Environment and Climate Change Canada)



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Future projections are consistent with observed trends. Climate change scenarios (in the absence of adaptation measures) project that the length of the winter road operating season will decrease from approximately 65 days in 2010 to 58 days by 2020 and 49 days by 2050 (with a 6 to 8 day margin of error per season).

Adaptation costs: It is possible that the winter road will remain viable through 2050, although there may be significant costs associated with flexible scheduling and increased construction and maintenance requirements. These costs are estimated in the range of $55 to 155 million[3] over a 35-year horizon.

There is also a significant risk of disruptions associated with late opening, early closure, or non-opening of the road. If the TCWR season length drops to fewer than 45 days, the road will no longer be able to accommodate an average season's demand. This has direct implications for mine production. In these circumstances, the most significant costs are likely to be associated with a shift to other modes of transportation. The total estimated cost of this scenario over 35 years is approximately $213 million, with a maximum cost of $1.8 billion (consisting mainly of production losses).

In summary, changes to the TCWR's operational season length create significant economic risks for both operators and users, assuming demand for the road increases or remains stable. Improved understanding of climate thresholds and associated costs for road owners and users may help to inform future economic and vulnerability assessments for winter roads.

Written based on findings from Perrin et al., 2015.

[3] These estimates represent net present values in 2015 dollars with a 4% discount rate applied.

4.3 ADAPTATION PRACTICES

Adaptation practices for roads vary by season and type of road (e.g., all-weather vs. winter). Generally, adaptation approaches for northern roads fall under three major categories: maintenance and monitoring practices; infrastructure planning and siting; and construction techniques and technologies.

4.3.1 MAINTENANCE AND MONITORING PRACTICES

4.3.1.1 All-weather roads

Ongoing monitoring of infrastructure conditions is important for identifying maintenance priorities, in preparation for gradual climatic changes and extreme weather events. In areas at risk of permafrost thaw, all-weather roads can be maintained through several methods, including clearing snow from vulnerable sections of roads built on permafrost (e.g., side slopes); conducting alternative routing assessments prior to reconstruction; and road-shoulder widening (Transportation Association of Canada, 2010). Culverts experiencing accelerated permafrost degradation can be replaced or expanded if runoff capacity is exceeded, and accompanying ditching/drainage may be enhanced in this event as well (Deton'Cho-Stantec, 2013). As permafrost thaws, all-weather roads that carry significant traffic – particularly heavy vehicles – will require greater maintenance compared to lower-traffic routes.

Monitoring can also mitigate the impact of forest fires, which often result in the closure of road segments. While some delays are inevitable, a public notification system can help mitigate bottlenecks and other effects of closure. Monitoring ground conditions after a forest fire is also important, as fires typically have an impact on underlying permafrost (Semeniuk, 2014).

4.3.1.2 Winter roads

Practices to maintain the integrity of winter roads include the pre-emptive removal of snow, as well as the construction and maintenance of snow caches (stockpiles of snow used as supporting material for degraded segments of winter roads). Snow removal allows freezing fronts to penetrate the ground faster, removing heat from the ground and promoting ice formation, while snow caches constructed near difficult land crossings allow overland sections to be rebuilt quickly (Deton'Cho-Stantec, 2013). To improve drainage, flattening side slopes on winter roads allows for the gentle removal of water away from the infrastructure (Deton'Cho-Stantec, 2013). Operational practices include spraying winter roads and bridges with water to thicken ice and delay closure. Towards the end of the operating season, some operators also restrict hauling to nighttime, when the ice sheet is stronger (Rawlings et al., 2009).

Several organizations have produced guiding documents to assist practitioners in the construction and maintenance of winter roads, including the Transportation Association of Canada (2011), the Government of the Northwest Territories (2015b and 2015c), the Canadian Standards Association Group (CSA, 2010), and the Standards Council of Canada's Northern Infrastructure Standardization Initiative (2015). These guidelines discuss general ice safety, ice behaviour under loading, ice-cover management, and end-of-season management (among others). Methods to deal with ice cracking are also covered in detail to ensure the safety of crossing frozen bodies of water; these risks to roads can be mitigated over the long term by establishing permanent crossings, including bridges over "choke points" (points of congestion created by the layout of a network) (Rawlings et al., 2009). For example, the Deh Cho Bridge, which crosses a 1 km-wide section of the Mackenzie River, is designed to eliminate seasonal disruptions to road transportation when ice bridges and ferry services become unavailable (Office of the Auditor General of Canada, 2011). For winter roads traversing ice, temporary culvert crossings may also be converted to permanent culverts, including systems to handle higher flows (e.g., stacked culvert systems) (Deton Cho-Stantec, 2013). Additionally, alternate routes can be considered when segments of roadway become unreliable (Deton Cho-Stantec, 2013) (e.g., increasing the use of barge transportation, or constructing more expensive all-weather roads) (Furgal and Prowse, 2008).

4.3.2 INFRASTRUCTURE PLANNING/SITING

The location of infrastructure is an important consideration for decision-makers, engineers, and planners in northern Canada. Critical baseline information includes data regarding local climate, permafrost conditions/sensitivity, and terrain constraints. Permafrost mapping and geotechnical monitoring, including assessments of soil type and ground ice content, are also conducted to avoid construction on overly sensitive ground (IMG-Golder Corporation Environmental Consulting, 2012). Improvements to permafrost databases and analysis of permafrost conditions could further support territorial governments in planning and decision-making, to permit greater understanding of methods to maintain transportation infrastructure on permafrost (Environment Yukon, 2009). Databases of this nature are maintained by the Geological Survey of Canada.

Many of the guidance documents discussed previously are also useful when identifying optimal locations for both all-season and winter roads. Additionally, land-use guidelines applicable to road construction have been developed. These encourage proponents to consider northern Canada's unique topography (i.e. pingos[4] and permafrost), drainage, and vegetation, along with the social and economic impacts of proposed roadways, during project planning and design (Aboriginal Affairs and Northern Development Canada, 2010).

[4] Referring to hills of rock and soil with ice cores that occur in permafrost-rich areas of the Arctic.

4.3.3 CONSTRUCTION TECHNIQUES AND TECHNOLOGIES FOR ALL-WEATHER ROADS

Several methods have been developed to preserve permafrost during construction (see Figure 10 and Case study 2) (Beaulac and Doré, 2006). These methods have different cost implications (Table 3) and functional objectives (limiting heat intake, extracting heat, and preserving the integrity of embankments).

Table 3: Comparing the applicability and relative cost of adaptation techniques for northern roads. (Source: Beaulac and Doré, 2006)

Technique	Continuous (Cold) Permafrost	Discontinuous (Warm) Permafrost	Sporadic Permafrost	Maintenance Required	Comments
Embankment thickening	$	$$	$$$	N/A	Application and cost depends on available material.
Insulation materials (polyurethane and peat)	$$$	$$$	N/R	Low	Bulky material needs to be imported. More effective if used in combination with heat extraction methods.
Snow sheds/ sun sheds	$$$	$$$	N/R	High	High level of maintenance.
Reflective surface	$$$	$$$	N/R	High	High level of maintenance.*
Air ducts	$$$$	$$$$	N/R	Moderate	Possible solution if well designed to avoid water accumulation in the ducts.
Thermosyphons	$$$$$	$$$$$	N/R	Moderate	More suitable for severe localized problems.
Air convection embankment	$$$$	$$$$	N/R	Low	Promising technique. Requires competent rock and capacity to produce specified material near construction site.
Heat drain	$$$$	$$$$	N/R	Low	Bulky materials need to be imported. Promising technique.
Geotextile and geogrid	$$$$	$$$$	$$$$	Low	Likely to reduce settlement and cracking problems.
Berms	$$$	$$$	N/R	Low	More effective if used in combination with heat extraction methods. Granular material needs to be available.
Pre-thawing	$$$	$$$	$$$	N/A	Possible solution if time permits.
Excavation/ replacement	$$	$$$	$$$$	N/A	Availability of granular material.
Snow removal	$$$	$$$	$$$	N/A	Labour intensive solution. Requires a service centre near the site to be protected.

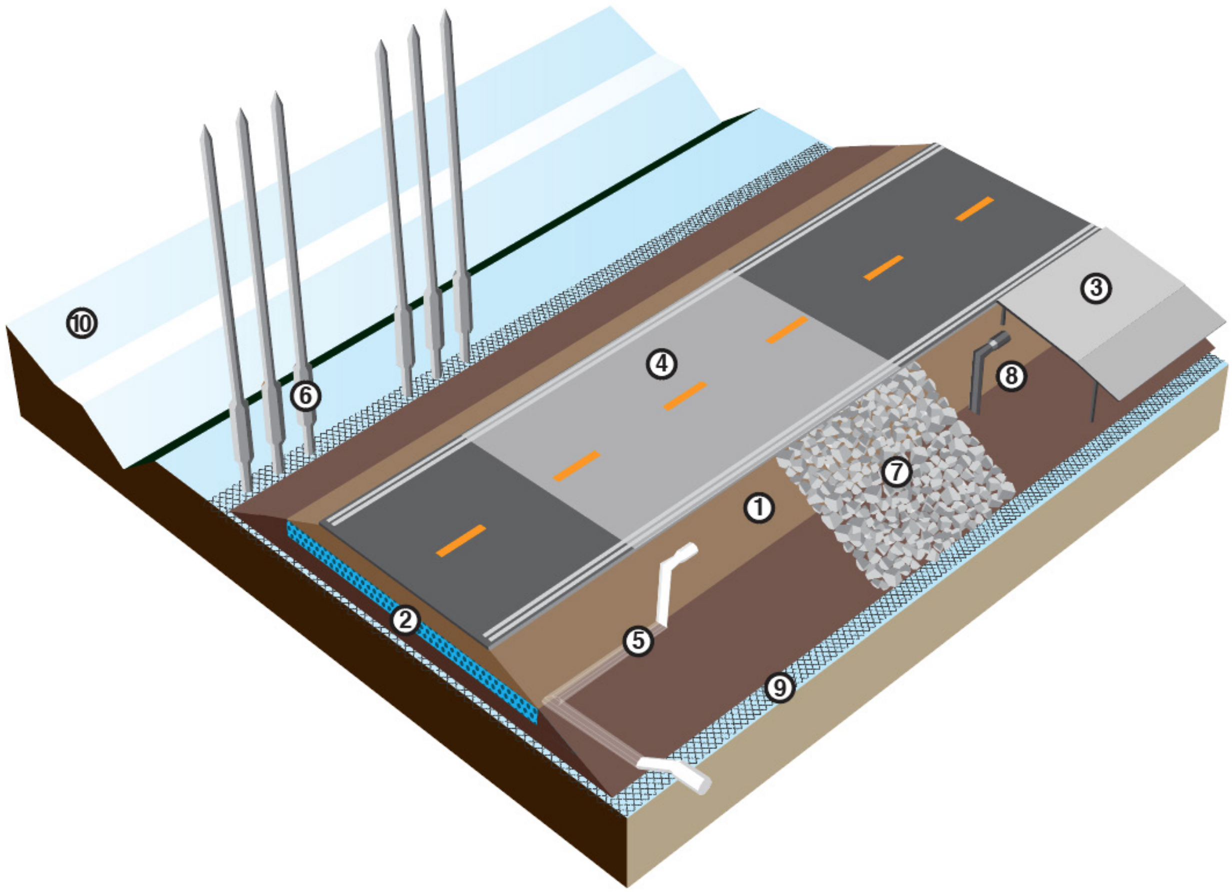
Suggested application. Application possible but not optimal

N/A: not applicable; N/R: not recommended

NOTE - $, $$, $$$, $$$$, $$$$$ is a relative scale, where $ presents the lowest relative cost and $$$$$ the highest.

**Reflective or high-albedo surfaces do not necessarily have high levels of maintenance. Levels vary depending on application.*

Figure 10: Conceptual illustration of adaptation techniques described in Sections 4.3.3. (Illustration created by www.soaringtortoise.ca.)



Methods to limit heat intake under roads include:

① **Embankment thickening** (e.g., increasing width and flatness) helps maintain permafrost conditions in cold or moderately cold regions (although not in relatively warmer northern regions, as the active permafrost layer may be too thick). This method reduces heat penetration underneath the embankment (IMG-Golder Corporation Environmental Consulting, 2012). The material used to supplement the embankment is an important consideration; for example, polystyrene demonstrates long-term resistance to moisture and compression on roads and runways (Beaulac and Doré, 2006).

② **Insulation materials** (including polystyrene, polyurethane, foamed concrete, and expanded polystyrene block) can be used to preserve the structural integrity of roadways and prevent permafrost from cooling in the winter (Montufar et al., 2011).

③ **Snow/sun sheds** protect embankment slopes from snow insulation, allow cold air to circulate during the winter, and eliminate direct solar radiation during the summer (Beaulac and Doré, 2006). Snow sheds have performed well in many locations, but require regular maintenance and present risks when overloaded with snow.

④ **Reflective surfaces (see also Figure 11),** such as painting paved surfaces white, reduce the absorption of solar radiation. While proven effective, this method carries a high initial cost and can decrease traction on curves, intersections, and in braking zones after periods of rain (Beaulac and Doré, 2006).

Figure 11: Test section of high-albedo (light-toned) surface treatment. (Source: Paul Murchison)

The most common methods to extract heat from the ground during winter include:

⑤ **Air convection ducts** are located under embankments to allow for heat extraction though natural convection (IMG-Golder Corporation Environmental Consulting, 2012). These may be oriented in the direction of the prevailing wind or constructed horizontally (Transportation Association of Canada, 2010).

⑥ **Thermosyphons** are passive cooling devices used to extract heat from the ground in winter and preserve the foundations of roads and buildings in 'warm' permafrost (see Figure 12). These systems, which have been used in the territories and northern Quebec, have been shown to cool the ground, raise the permafrost table, and stabilize foundations over time (Montufar, et al. 2011). While there have been problems with poorly functioning thermosyphons in the territories, these have been attributed to poor installation and maintenance. Figure 12 presents the mechanics behind this technology, and Figure 13 illustrates a thermosyphon in use at Inuvik Airport.

All varieties of thermosyphons (e.g., thermopiles, sloped-pipe thermosyphons, and flat-loop evaporator pipe thermosyphons) work on the same principle: a two-phase convection device extracts and discharges heat from the ground, cooling the permafrost. In winter, when the air is colder than the ground, thermosyphons cause gas in the above-ground pipe to condense and move to the base of the underground pipe. The cold air then drops the pipe's fluid pressure, causing evaporation and completing the exchange of heat. During summer, low ground temperatures are maintained by a layer of insulation (Holubec, 2008).

Figure 12: Illustration of heat exchange in a thermosyphon. (Source: Igor Holubec)

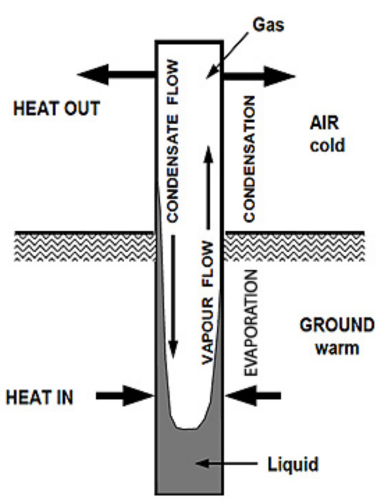


Figure 13: Flat-loop thermosyphon foundation at an airport maintenance garage in Inuvik, NT. (Source: Igor Holubec)

⑦ **Air convection embankments** refer to the creation of embankments with clean, coarse, and poorly-graded rock (IMG-Golder Corporation Environmental Consulting, 2012). The resulting large, interconnected voids assist in air convection, extracting heat while maintaining the structural integrity of the embankment (IMG-Golder Corporation Environmental Consulting, 2012).

⑧ **Heat drains** consist of permeable geocomposite material and a thin corrugate plastic cover placed underneath an embankment. These allow for heat extraction during winter as air flows through the layers (Montufar et al., 2011). Heat drains have been found to significantly reduce ground temperatures (Montufar et al., 2011).

Methods to enhance the stability of embankments include:

⑨ **Geotextiles** (i.e. permeable fabrics) reduce thaw-settlement by separating embankment fill and underlying soil, and by preventing embankment "spreading". These materials are typically applied to areas that have a deep active layer and are poorly drained, in which mixing of subgrade soil and embankment fill is likely (Transportation Association of Canada, 2010).

⑩ **Berms** (often with gentle slopes) protect low embankments from excessive thawing (Beaulac and Doré, 2006) by providing a physical barrier to the accumulation of snow, much like a snow fence (IMG-Golder Corporation Environmental Consulting, 2012).

Additional reinforcement techniques involve pre-thawing permafrost to reduce the effects of freeze-thaw settlement, and excavating/replacing ice-rich permafrost with fill (IMG-Golder Corporation Environmental Consulting, 2012).

CASE STUDY 2

CASE STUDY 2: TESTING TECHNIQUES TO PREVENT PERMAFROST THAW

An experimental road section along a segment of the Alaska Highway was built in 2008 to test engineering techniques designed to prevent permafrost thawing under road infrastructure. The test site, 5 km southeast of Beaver Creek (Yukon) in a zone of discontinuous permafrost, was divided into twelve 50-m sections, including an undisturbed control section. Techniques being tested include: crushed-rock air convection embankments, heat drains, thermo-reflective air convection sheds, longitudinal air convection ducts, reflective aggregate surface treatments, grass-covered embankments, and plowing snow on side slopes (described in previous sections).

Research is ongoing, but results from the first three years of monitoring suggest that some techniques have the potential to promote permafrost formation (or ground refreezing) and active-layer thinning, preserving the permafrost or reducing the rate of degradation (Malenfant-Lepage et al., 2012).

The three most promising techniques include longitudinal air convection ducts, thermo-reflective air convection sheds, and air convection embankments. These techniques utilize the "chimney effect," wherein cold air is allowed to sink into the embankment and warm up. Lighter and warmer air is then released upward, removing embankment heat and lowering ground temperature. The light-colored aggregate has also shown strong potential to reduce subsurface warming. All seven techniques yielded results superior to the "do-nothing" scenario.

Results also suggest that the flow of water in the soil is a key factor in the dynamics of heat transfer and permafrost degradation at the test site (De Grandpré et al., 2012). A drainage ditch was excavated in the fall of 2010 to lower the water table, decrease the water flow and reduce the amount of heat conveyed through the road embankment. Since then, the water level and flow have decreased significantly. Models are currently being developed to provide a better understanding of the heat transfer and extraction processes generated by these techniques.

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One of the major conclusions of this work is that no technique can be efficiently implemented without a thorough assessment of the surrounding terrain at the appropriate scale. This includes information on the site's ground composition (including ice distribution and volume); thermo-physical properties; history; specific processes driving or sustaining permafrost; and the drainage network's sensitivity to change.

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5.0 RAIL TRANSPORTATION

Rail plays a smaller role in the territories than in other Canadian regions, but does provide important services. Similar to road infrastructure, rail track is particularly vulnerable to the effects of permafrost degradation. Thawing may cause heaving, sinkholes, potholes and settlement issues for railways in northern Canada (IMG-Golder Corporation Environmental Consulting, 2012). Associated adaptations can either be active, removing heat from the embankment, or passive, reducing heat absorption (Ferrell and Lautala, 2010). Some engineering solutions for roads can also be applied to rail infrastructure, including embankment widening and the installation of thermosyphons, snow sheds, and insulation. The following methods may also be used:

- **Ventiduct embankments** refer to pipes placed alongside the traditional soil embankment, allowing air to pass through the embankment and drawing heat from the soil. In order to reduce heat absorption of the soil during the summer months, these pipes can be sealed (Ferrell and Lautala, 2010).

- **Stone embankments** are used to create pore space within embankments and allow air to penetrate the structure and natural convection to remove heat from the subgrade (Ferrell and Lautala, 2010).

- **Snow/sun sheds** reduce snow accumulation and solar radiation on the embankment. They can also reduce water infiltration and permit airflow, removing heat from embankment surfaces (Ferrell and Lautala, 2010).

Extreme weather can damage embankments and create washouts and soil/rock slides, which may result in rail line closures (IMG-Golder Corporation Environmental Consulting, 2012). The incorporation of higher-capacity culverts for embankments and bridges can mitigate the effects of seasonal drainage and extreme events (IMG-Golder Corporation Environmental Consulting, 2012). Some rail companies also have winter operating plans that include snow removal, sanding and salting, track and wheel inspections, temporary slow orders, and personnel training initiatives (Lemmen and Warren, 2004). Although rail transport is limited in Canada's North, greater rail infrastructure development may be feasible in the future (Yukon Government, 2013). For a more detailed assessment of impacts and adaptations related to Canada's rail sector, refer to other regional chapters.

6.0 AIR TRANSPORTATION

6.1 CLIMATE IMPACTS ON AIR TRANSPORTATION

For communities in the North, many which are not connected via roads, disruptions to aviation can significantly impact mobility and restrict the supply of goods. For example, in 2014, when Canadian North grounded all of its flights to and from Iqaluit during a blizzard, passengers in Pangnirtung, Qikiqtarjuaq, Hall Beach, Igloolik, Cape Dorset, Pond Inlet, and Clyde River were affected (CBC News, 2014).

Climate stressors that have an impact on air transportation in the North include fog, freezing rain, heavy precipitation, high winds, and blowing snow. For example, extreme fog and condensation can delay flights and shut down airports, particularly in coastal communities (Klock et al., 2001). While data on fog and condensation is limited, firsthand accounts indicate that fog events have become more frequent in the territories, resulting in reduced visibility at airports (Deton'Cho-Stantec, 2013). With few communities possessing navigational systems, this makes approaches to airports more challenging. For example, as of 2013, eight airports in the Northwest Territories did not have the navigational systems in place to assist pilots in landing during their approach. Thus, under extreme fog conditions, these airports are forced to suspend operations. For example, the airport in Wekweeti, Northwest Territories, was shut down for a week in September 2011 due to dense fog (Deton'Cho-Stantec, 2013).

Rain and freezing rain can also have an impact operations by decreasing traction on runways and taxiways, necessitating the use of de-icing products prior to take-off. Loss of friction and flooding of runways can also cause flight cancellations, as was the case in Inuvik in 2011 when ground personnel were unable to keep the runway clear (Deton'Cho-Stantec, 2013). In addition, similar to all-weather and winter roads, changing air temperatures can impact the structural integrity of permafrost under runways and taxiways.

Gravel runways and taxiways also present unique challenges for aviation in northern Canada, as they can become significantly weaker following periods of heavy precipitation or spring thaw (Transport Canada, 2016). The weakening of these surfaces may limit or completely halt runway operations (Transport Canada, 2016). This exacerbates another capacity issue: many airstrips in northern Canada can only accommodate relatively small aircraft (Parliament of Canada, 2011).

Table 4: Overview of climate and extreme weather impacts on air transportation.

Climatic factor	Impact on aviation
Air Temperature	Permafrost degradation can damage and degrade runways/taxiways (Government of Nunavut et al., 2011).
Snow	Increased snowfall may cause flooding in the thaw seasons, damaging permafrost under runways/taxiways (Deton'Cho-Stantec, 2013). Blizzards, blowing snow, and winter storms can reduce visibility and delay flight operations (e.g., via the accumulation of snow on runways) (Hanesiak et al., 2009).
Rainfall	Increased rainfall can reduce traction on runways/taxiways (Best, et al., 2014). Intense periods of freezing rain can cause delays to flights and could cause airplanes to experience issues with braking and sliding off airstrips (IMG-Golder Corporation Environmental Consulting, 2012).
Fog	Increased fog episodes may require additional training and procedures for airport personnel in order to ensure safety (Deton'Cho-Stantec, 2013). Intense periods of fog can delay flights until visibility improves (Deton'Cho-Stantec, 2013).

6.2 FUTURE RISKS

Rising air temperatures will continue to affect permafrost conditions, presenting a risk to the integrity of both gravel and paved runways. Increased precipitation may lead to reduced traction and visibility. These changes will increasingly affect the planning, design, and maintenance of airports in the North.

Finally, weather extremes associated with increasing and varying wind speeds, are expected to affect airports. For example, high winds contribute to severe blizzards and snowstorms that limit visibility and have the potential to slow down airport operations. These issues are summarized in Table 4.

6.3 ADAPTATION PRACTICES

Methods to address permafrost degradation affecting paved runway and taxiway issues are similar to those for all-weather roads given the similarities between these types of infrastructure (see Case study 3). Generally, airports in the North are reacting to these changes in the absence of long-term strategic planning.

Airports that have gravel runways can correct for ground settlement resulting from permafrost thaw by adding material to the runway/taxiway. Gravel is easier to resurface/grind up and replace in comparison to pavement (Deton'Cho-Stantec, 2013). Gravel runways can also be reconstructed without having to transport heavy specialized equipment to the location.

In cases of heavy precipitation, grooving on paved runways and taxiways can improve traction and drainage. This method has been applied at Norman Wells Airport in the Northwest Territories in order to increase drainage and improve surface friction (Deton'Cho-Stantec, 2013). The cost of grooving varies depending on the type of runway material (e.g., concrete or asphalt), the type and size of aggregate (e.g., limestone, gravel, etc.), the age and condition of the runway surface, the size of the project, and local factor costs (e.g., fuel costs, support equipment, mobilization costs) (Best et al., 2014). While runway grooving has been shown to enhance water drainage, improve friction, and reduce sanding requirements, this technique is relatively costly (Deton'Cho-Stantec, 2013). In the event that grooving and/or sanding are not sufficient to increase traction and improve drainage, heavy machinery has been employed to remove pooling water.

Airports have been increasingly applying sand to surfaces in order to counter the effects of standing water and freezing rain. Sand requirements have been growing – for instance, Norman Wells Airport increased its use of sand from 10 to 15 tonnes per year prior to 2000 to over 150 tonnes per year in 2012 (Deton'Cho-Stantec, 2013).

Airports attempt to mitigate the impacts of high snowfall on permafrost (thermal insulation) by removing snow as quickly as possible. In order for airplanes to operate during periods of heavy snowfall, airport personnel continuously clear runways and taxiways to allow airplanes to take off and land safely.

De-icing agents are used commonly at northern airports to address aircraft wing contamination (e.g., by ice, snow, or freezing rain) (Deton'Cho-Stantec, 2013). De-icing agents can also be used to clear contaminants from runways and taxiways. These products contain glycol, and it has been suggested that runoff from these compounds may result in warmer ground temperatures and other environmental impacts. There have been calls for the development of a glycol management strategy as the volume of glycol used at northern airports increases (Deton'Cho-Stantec, 2013).

CASE STUDY 3

CASE STUDY 3: INFRASTRUCTURE IMPROVEMENTS AT IQALUIT INTERNATIONAL AIRPORT

Iqaluit International Airport is extremely important to communities in Nunavut given the region's lack of road access. When the airport was constructed in 1942, little was known about the underlying permafrost and its importance to the safety and viability of airport operations. However, many problems related to permafrost – including runway stability issues stemming from thaw settlement of ice-rich soils – have occurred at the airport over its lifespan. In tandem with the need for expansion and facility replacement, permafrost issues prompted the development of an improvement plan by public and private partners.

In 2013-2014, the *Iqaluit International Airport Improvement Project* was initiated; by then, the importance of understanding the nature, location and influence of permafrost degradation on infrastructure was well-understood. A number of research projects were undertaken, employing a variety of techniques – including ground-penetrating radar, permafrost core analysis, surficial mapping, and remote sensing – to generate site-specific knowledge about permafrost properties and model interactions among permafrost, climate, and airport infrastructure (both existing and proposed). A key finding of this work is that permafrost tends to be subject to greater warming under pavement than embankments (and other "naturalized" surfaces).

The data collected has been used to inform infrastructure decision-making. Maps were produced to identify potentially-problematic locations for existing and proposed infrastructure (e.g., thaw-sensitive soils and/or difficult terrain for construction); a taxiway was relocated with an insulated barrier to reduce permafrost damage; the importance of removing thick snow cover in key areas was recognized; thermosyphons were installed beneath airport buildings; and drainage was improved to reduce the infiltration of surface water into permafrost. Overall, informed engineering and operational decisions have been made at the airport with respect to the integrity of the underlying permafrost.

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7.0 MARINE TRANSPORTATION

7.1 CLIMATE IMPACTS ON MARINE TRANSPORTATION (INCLUDING LAKES AND RIVERS)

Climate factors affecting marine transportation in northern Canada include: changing patterns of sea ice; precipitation events; strong and variable winds; and changing water levels.

As discussed in Section 4, recent decades have seen dramatic changes in the Arctic sea-ice regime (Bush et al., 2014; Dawson et al., 2014). While decreases in the extent and duration of sea ice present potential economic opportunities in terms of increased marine traffic and shipping-season length, several barriers remain for Arctic shipping expansion. For example, the high year-to-year variability of ice in the Canadian Arctic has significant impacts on marine insurance, investment, and ship construction standards (Ellis and Brigham, 2009). Few year-round commercial navigational vessels currently operate in the Canadian Arctic (with the exception of nuclear icebreakers) (Ellis and Brigham, 2009).

Sea ice changes are also associated with coastal erosion, navigation problems, and infrastructure damage. Changing distributions of multi-year ice have led to ice detaching and migrating into unexpected areas, creating obstacles and hazards for cargo vessels (Deton'Cho-Stantec, 2013). This has implications for search and rescue capacity, winter shipping, passenger safety, and coastal shipping (particularly near Newfoundland). Currently, large icebergs are tracked using satellite and aerial surveys to limit potential complications (National Snow and Ice Data Centre, 2016).

Decreasing sea ice also creates larger expanses and longer durations of open water, which worsens the impacts of storm and wind events, disrupts shipping routes, and increases the difficulty of maneuvering through narrow channels (IMG-Golder Corporation Environmental Consulting, 2012). Changing ice conditions can also increase the vulnerability of northern communities: recent ice conditions in the Canadian Arctic have held up the annual resupply of fuel and goods in some communities in Nunavut, for example (CBC News, 2015a).

For port operations, storm surge and extreme rain events can lead to flash floods, disrupt shipping and present risks to human safety. For example, storm surges have flooded port facilities in Tuktoyaktuk, temporarily suspending operations (Deton'Cho-Stantec, 2013). Strong winds associated with storms can also cause navigational challenges, especially in narrow channels and dockings, due to ice jams, ice choke points (i.e. a point of congestion created by ice), and wave action (IMG-Golder Environmental Consulting, 2012).

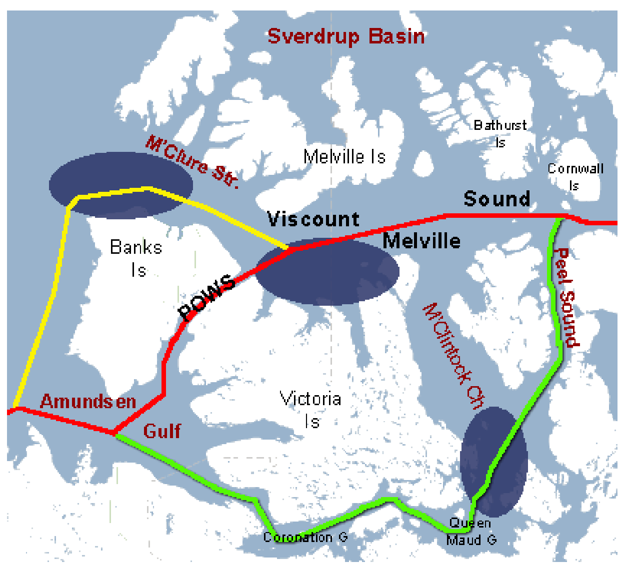
For river transportation, lower water levels have required the use of lighter barges or smaller loads to maintain safety standards, in some cases disrupting operations (Deton'Cho-Stantec, 2013). For example, low water levels in the Mackenzie River have delayed the shipment of goods to northern communities in recent years, leaving residents without access to necessary goods and materials until shipments could be secured through more costly alternatives (such as air or road transport) (CBC News, 2015b and 2015c). Permafrost degradation along river banks and sides of valleys has also caused slumping and route obstructions in some locations, forcing river transporters to adjust their routes (Deton'Cho-Stantec, 2013).

7.2 FUTURE RISKS AND OPPORTUNITIES

The Northwest Passage is not expected to become a viable route in the near future due to "seasonality, ice conditions, a complex archipelago, draft restrictions, chokepoints, lack of adequate charts, insurance limitations, and other costs" (IMG-Golder Environmental Consulting, 2012) (see Case Studies 4 and 5). Throughout the northern region, destination shipping is anticipated to increase to accommodate expanding resource development, growing communities, and increasing tourism. However, operational costs will remain high due to the presence of ice and associated expenses (Ellis and Brigham, 2009).

Over the longer-term, climate projections forecast that by midcentury, changing sea ice conditions will enable new routes for ice-strengthened ships over the North Pole and new routes through the Northwest Passage (Smith and Stephenson, 2013). If and when the Northwest Passage becomes a viable shipping route, services such as re-fueling stations, tugs, and emergency repair will need to be carefully considered. Figure 14 identifies various routes through the Northwest Passage.

Figure 14: Northwest Passage routes and ice choke points (Mudge et al., 2011). The deepest route is presented in red, shallow in green, and the least-travelled in yellow. In addition, navigation choke points are shown in blue. POWS is Prince of Wales Strait. (Source: ASL Environmental Sciences Inc.)



CASE STUDY 4

CASE STUDY 4: HAS THE NORTHWEST PASSAGE BECOME VIABLE?

On September 19, 2014, icebreaking bulk-carrier *MV Nunavik* made history by transporting 23,000 metric tons of nickel concentrate from Deception Bay, QC to Bayuquan, China through the Northwest Passage. Prior to this historic voyage, only one full cargo ship had ever transited the Northwest Passage, and none had ever done so unassisted. In recent years, traffic in the Northwest Passage has increased but has been dominated by adventure tourists and private yachts. Full commercial cargo transits have been extremely limited, despite the route being touted for its decreased distance, and potential for fuel and cost savings. The *Nunavik* transit took 27 days, about 15 days shorter than a passage through the Panama Canal. The DNV-GL Polar Class 4 vessel, powered by a slow-speed diesel engine capable of generating nearly 30,000 horsepower, is one of the most capable ships globally to withstand ice-infested Arctic waters. The ship is equipped with a sophisticated 'iceNav' system with virtual marine radar to detect potential ice hazards and determine efficient and safe routes.

This historic voyage, along with the first cargo trip made by the *MV Orion* in 2013, proves that the Northwest Passage has the potential to be a viable shipping route. However, the fact remains that only two cargo ships have made the fabled journey – and for good reason. The passage remains extremely risky to navigate, considering its highly unpredictable ice and weather conditions, poorly-charted waters, and a lack of vessels with sufficient structural and technical capabilities. It is unlikely that the Northwest Passage will become a major shipping route in the near-to-medium term (Mudge et al., 2011).

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CASE STUDY 5

CASE STUDY 5: RESOURCE DEVELOPMENT IN THE BEAUFORT SEA REGION

Reduced sea-ice cover as a result of a changing climate has prompted the petroleum and shipping industries to view the western Arctic waters with new levels of interest. The Beaufort Sea Region (water north of Canada and Alaska) is estimated to contain 10 billion barrels of oil (Houseknecht et al., 2012), and oil and gas companies currently hold licenses for nearly $2 billion (CAD) worth of exploration work over the next 10 years (Ellis and Brigham, 2009).

There remain several challenges associated with resource extraction in the Arctic, including a need to improve safety (i.e. greater search-and-rescue and disaster-response capacity) and supporting infrastructure, as well as issues associated with changing and difficult-to-predict ice conditions (IMG-Golder Corporation Environmental Consulting, 2012). There are also other issues relating to the increasing season and extent of open water, including more frequent dangerous fog conditions, as well as greater wind, wave, and erosion hazards. These issues are problematic for an area lacking complete hydrographic charts.

Coastal erosion is also affecting Tuktoyaktuk Island, which protect Tuk Harbour – the planned supply and support base for offshore activity. The island has been receding at a rate of approximately 2m/year. "If the island erodes away or is breached, there is the potential for greater negative effects such as erosion of the inner harbour coastline or damage to infrastructure during storm surges or normal wave action, especially with rising sea levels" (Mudge et al., 2011). Ironically, the climate changes that are opening the Beaufort Sea to exploration and shipping are also likely to make exploration challenging.

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While reduced sea ice may result in greater marine activity over the long term, marine infrastructure and operations will remain vulnerable to decreasing sea ice and changes in sea level throughout the 21st century. Despite rising sea levels globally, most of northern Canada is projected to experience a decline in relative sea level due to glacial isostatic adjustment (introduced in Section 4). As a result, some areas of northern Canada could face navigation issues such as reduced under-keel depths, as well as difficulties accessing coastal infrastructure due to lower water levels (Mudge et al., 2011). Trip cancellations and lower load capacities as a result of unsafe vessel keel depths affect the delivery of critical supplies from regional distribution centres to rural communities (White et al., 2007).

Exceptions to this trend include Tuktoyaktuk and Sachs Harbour (in the Northwest Territories), which will experience sea-level rise (James et al., 2014). The risks associated with higher sea levels include greater coastal erosion, more intense wave action/sea spray, increased exposure of dock decks, and higher waves (affecting structures) (IMG-Golder Corporation Environmental Consulting, 2012). Issues associated with wave erosion and storm surge will increase in these areas as well, as a result of decreased sea-ice cover (creating larger stretches of open water) and sea level rise (Case study 5).

Increased coastal erosion will necessitate more frequent and costly maintenance and replacement of shoreline and coastal infrastructure (Couture et al. 2015). Examples of additional risks from sea level rise include increased wave height (resulting in structural impacts) and increased corrosion of infrastructure designed to withstand specific sea level conditions (Mudge et al., 2011). Conversely, increased under-keel depths in these regions may present opportunities for greater vessel capacity.

In short, the opportunities associated with opening transportation routes also come with challenges related to safety (i.e. greater risks associated with wind, wave, and ice action) and environmental protection (i.e. greater shoreline erosion).

7.3 ADAPTATION PRACTICES

Adaptation approaches for marine transportation can be categorized into practices for vessels and navigation, and those for coastal infrastructure.

7.3.1 ADAPTATIONS FOR VESSELS AND NAVIGATION

Commercial shipping in the Arctic over the near term will be mainly limited to seasonal passages using vessels suitable for ice conditions that are variable and unpredictable from year to year (White et al., 2007; James et al., 2014; IMG-Golder Corporation Environmental Consulting, 2012). To mitigate the risks posed by changing ice conditions, many companies have carried out winter-operation risk assessments and ship-specific winterization procedures (Patterson, 2012). In many cases, damage to vessels can be prevented by careful route planning and operational prudence (Deton'Cho-Stantec, 2013). Vessels are often outfitted with additional navigation and communications equipment to monitor ice conditions; these include iceNav systems incorporating advanced marine radar, enhanced target detection radar, and satellite communication technologies for acquiring ice charts and electronic chart viewers (Patterson, 2012). Ships can also be retrofitted with ice-breaking equipment (Journeaux, Assoc., 2012). If sea ice has accumulated in a docking area, a tugboat or the ship can maneuver back and forth to break the ice (Journeaux, Assoc., 2012). However, the availability of tugs can be an issue. Risks to propellers and rudders in shallow waters (e.g., during community re-supply) can be mitigated by using larger and more durable cargo vessels, and offloading to smaller and lighter vessels along problematic stretches of coastline (a process known as "lightering") (Deton'Cho-Stantec, 2013).

The Sea-ice Monitoring and Real-Time Information for Coastal Environments (SmartICE) system is an innovative example of an enabling technology that can be used to provide ships travelling through Arctic waters with accurate and timely information about ice conditions (Fournier and Caron-Vuotari, 2013). Developed by the Nain Research Centre, SmartICE combines remote sensing and traditional Inuit knowledge to provide relevant and accessible information on sea-ice thickness, concentration, and roughness to determine safety based on mode, length of trip, trip type (e.g., recreational vs. industry), and other factors (NAIN Research Centre Kaujisapvinga, 2015).

Vessels travelling along rivers often need to reduce cargo loads to allow for travel through shallow coastal areas. In the future, reduced water levels may further affect the cargo capacity of low-draft barges (Deton'Cho-Stantec, 2013). In this case, adjusting the loads of some barges may not be sufficient – route adjustment may be needed in order to traverse some areas. Along the Mackenzie River, barges have adjusted their routes and reduced speeds while travelling through difficult waters (Deton'Cho-Stantec, 2013).

Governments have an important role to play in supporting marine navigation. The following services have been identified as critical to safe marine transportation: the production of navigational charts; the deployment and maintenance of navigational aids; the provision of weather and ice information and ice-breaking services; and the surveillance and monitoring of marine traffic (Office of the Auditor General, 2014). In addition, the International Maritime Organization (IMO) has developed a Polar Code, covering a full range of design, construction, equipment, operational, training, search and rescue and environmental protection matters applicable to ships operating in the waters surrounding the two poles (International Maritime Organization, 2016).

7.3.2 ADAPTATIONS FOR MARINE FACILITIES

For marine infrastructure in the western Arctic vulnerable to storm surges and coastal erosion, practices to reduce risks may include mapping areas most likely to be affected and constructing defenses to limit damage. Coastlines can be protected via the construction of barriers composed of sandbags, sunken vessels, and rocks and gravel to reduce the impacts of erosive wave action (IMG-Golder Corporation Environmental Consulting, 2012). However, while sea defense structures help to protect the coast, changes in coastal sediment dynamics which may occur as a result of construction or a changing climate are important considerations. In some cases, it may be necessary to relocate shore-based cargo resupply infrastructure (e.g., fuel manifolds and piping infrastructure) to prevent damage (Deton'Cho-Stantec, 2013). Studies of sea ice behavior can help determine appropriate dock locations and shipping lanes. Docks could then be outfitted with systems to minimize the development of sea ice. In the immediate future, piers and mooring structures may require repair and reconstruction as a result of sea-ice impacts (IMG-Golder Corporation Environmental Consulting, 2012).

For facilities along rivers, several adaptation practices have been applied to date. Along the Mackenzie River, mooring points have been moved so that barges may offload in stable locations closer to shore where less erosion has taken place. Gravel ramps have also been re-established to replace eroded materials in some locations (Deton'Cho-Stantec, 2013).

In some cases, it may be necessary to dredge harbours should water levels decline. This has been done in several northern communities in the past, including Tuktoyaktuk and Hay River (on Great Slave Lake), to cope with shallow water conditions. However, dredging operations require substantial resources that can serve as barriers to many communities. For instance, the cost to dredge a deeper channel in Tuktoyaktuk to allow the passage of cargo vessels has been estimated in excess of $100 million (Deton'Cho-Stantec, 2013). There may also be a greater need for transferring cargo between vessels of different sizes to allow passage in shallow harbours, and during high wind events. However, this process slows down ships transporting goods to further locations (Deton'Cho-Stantec, 2013).

8.0 INFORMATION GAPS

There are a number of gaps in available information related to the determination of climate impacts on transportation in Canada's northern region. These include reliable and relevant climate information; available training, guidance and tools; and technical information for infrastructure.

Regarding climate information, territorial governments and others have expressed interest in developing regional climate change scenarios in order to improve understanding of future conditions (Environment Yukon, 2009). In a survey of mining and transportation practitioners in the Yukon, participants also identified the need for downscaled climate data – some expressed concern that the data they were using was not appropriate for their area. Projections related to climatic elements such as rain-on-snow events, snow and permafrost interactions, and relationships between snowmelt and rain are in particular demand (Northern Climate ExChange, 2014b). There are two notable challenges to obtaining these climate change scenarios for the territories: limited baseline data is available at the local level, and capacity in the northern territories is restricted by limited financial and human resources (Government of Nunavut et al., 2011). The limited number of weather stations in the North and short duration of climate records also present challenges to developing local climate change scenarios. Practitioners have also indicated they lack practical and user-friendly guidance tools for using climate data, as well as training for practitioners and decision-makers (Northern Climate ExChange, 2014b).

Further development of building standards, codes, and community planning information that takes into account projected changes in climate have also been identified as desirable. These would need to consider existing technical guidance on factoring in future climate changes when building on permafrost (Auld et al., 2010), and expand upon the Standards Council of Canada's Northern Infrastructure Standardization Initiative that has developed standards for: 1) thermosyphon foundations (CSA Group, 2014a); 2) moderating the effects of permafrost degradation on building foundations (CSA Group, 2014b); 3) managing changing snow-load risks for buildings in Canada's North (CSA Group, 2014c); and 4) drainage-system planning, design and maintenance in northern communities (CSA Group, 2015). Relevant variables include ground ice content as well as experienced and projected ground temperatures and permafrost thicknesses. Such information could be used to develop maps identifying areas suitable for infrastructure development (Champalle et al., 2013), and be used at regional and local scales to determine areas with low, moderate, or high levels of vulnerability (Calmels et al., 2015).

Improved channels for information-sharing among northern practitioners and residents is another important gap. Tools such as the Arctic Adaptation Exchange portal, developed during Canada's Arctic Council Chairmanship, help facilitate the sharing of adaptation best-practices among circumpolar communities (Arctic Adaptation Exchange, 2014).

For marine transportation, updating geospatial databases to account for the challenges and opportunities presented by a changing climate is important. This involves updating maps and navigational charts to reflect changes in ice coverage and traffic, as well as providing the marine community with information and charting strategies to deal with future climate uncertainty. Publicly available data on coastal erosion would be particularly beneficial (Champelle et al., 2013). For example, the Coastal Information System (maintained by the Geological Survey of Canada) provides qualitative coastal changes based on multiple years of video and aerial photography that can be used by communities experiencing coastal change (Couture et al., 2015). In addition, improved hydrological monitoring would allow better understanding of the impacts of climate change on runoff volumes, evaporation rates, and water levels, and would benefit community resupply operations in the Northwest Territories. Lastly, improved water level monitoring, including a water level-monitoring network and ice/debris advisory service, would benefit barge operators throughout the region (Deton'Cho-Stantec, 2013).

For land-based corridors, more accurate mapping of geographic sensitivities (e.g., slope stability) and hazards would support more appropriate infrastructure.[5] As surface transportation becomes more costly and difficult to construct and maintain in warmer temperatures, new transportation technologies may also need to be considered for northern Canada. Air ships have been studied as an alternative to surface transporting for many goods (including food) to northern communities and resource extraction sites – prototypes with 10- and 70-tonne load carrying capacity are being developed, with testing underway for specific applications (including use in remote northern regions) (Canadian Shipper, 2013). However, timelines for the uptake of this technology remain uncertain. Finally, while information on adaptation techniques and practices for roads (both winter and all-weather) in northern regions is readily available, further risk and adaptation research for other modes would be useful.

5 See: Blais-Stevens and Behnia (2015)

9.0 CONCLUSIONS

Given the degree of climate change observed and projected for Canada's North, significant research has been undertaken to assess opportunities and challenges for transportation in the region. This chapter has documented some key findings emerging from this growing body of work. While existing research can help governments, communities, and practitioners prepare for future conditions, gaps remain to support the efficient and reliable movement of goods and people in the North, now and in future.

This chapter has described the vulnerabilities of northern transportation infrastructure and operations to the impacts of climate change. It has also identified adaptation actions (both existing and potential) to address these issues. Underlying themes include the implications of permafrost degradation for transportation infrastructure (including all-weather roads, winter roads, and runways/taxiways); challenges to northern shipping resulting from greater sea-ice movement, storm surges and coastal erosion; and the difficulties of dealing with climate change given the region's vast size and limited human and financial resources.

As discussed throughout this chapter, numerous practices – including adaptive maintenance practices, technological investments, and construction techniques – have been implemented by both the public and private sectors to reduce the impacts of a changing climate on people and supply chains. Adaptive maintenance requires constant and consistent information-gathering (such as ensuring snow removal equipment is in place and monitoring weather conditions). Technological investments can range from relatively simple (e.g., pavement grooving to improve traction on runways/taxiways) to more significant investments (e.g., installing thermosyphons). Adaptive construction requires identifying the nature of the risk (e.g., thawing permafrost) and choosing the appropriate technique (i.e. reinforcing embankments with geotextiles). Regardless of the approach, it is clear that the transportation sector in Canada's North will be faced with significant changes to operating conditions over both the short and long term, and that it has begun to adapt accordingly.

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4 · British Columbia

CHAPTER 4: BRITISH COLUMBIA

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KEY FINDINGS

- **Transportation systems in British Columbia have demonstrated vulnerability to extreme weather and changes in climate.** Impacts of particular concern include those associated with:
  - Extreme precipitation, such as atmospheric river (Pineapple Express) events, affecting road and rail networks, marine transportation lanes, and airport facilities;
  - Sea level rise and storm surge, increasing the risks of flooding and damage to fixed coastal infrastructure, including Vancouver International Airport, Sandspit Airport on Haida Gwaii, and the Port of Vancouver;
  - High winds, affecting marine transportation lanes; and,
  - Visibility issues, affecting airport operations, particularly in the British Columbia interior.
- **Land transportation routes within British Columbia often occupy restricted corridors through mountains and along coastlines.** In these settings, flooding (associated with extreme precipitation or snowmelt) and slope failures have resulted in infrastructure failures to road and rail systems in the past. Events that have affected one of these modes have typically also affected the other.
- **While previous efforts to reduce climate risks to transportation systems were often reactive, and based on historical information, there is indication that this is changing**. Transportation entities are now inclined to become involved in broader future focused climate change studies and to incorporate these finding into their systems.
- **Climate change vulnerability assessments and revised and updated infrastructure design criteria can improve planning and adaptation efforts for British Columbia's transportation infrastructure.** The provincial government has conducted vulnerability assessments for highway systems and continues to monitor and assess sea level rise. The British Columbia Ministry of Transportation and Infrastructure is one of the first jurisdictions to require infrastructure design work for the ministry to include climate change implications.
- **Given the interconnectedness of transportation networks in British Columbia, there is opportunity to share research, risk analysis, and adaptation best practices across modes.**

1.0 INTRODUCTION

British Columbia is Canada's third-largest and most westerly province, encompassing more than 95 million hectares of land and freshwater (10% of Canada's land surface) and 27,200 km of coastline (KnowBC, 2016). Its geography is rugged – vast, snow-covered mountain ranges stretch along the coast and through eastern and southern regions of the province, while the central interior and northeast are characterized by valleys and broad plains. Provincial transportation systems must contend with many shoreline inlets, tight corridors traversing mountain ranges with few major passes, and long distances between population centres. Economic activity and opportunity is distributed across the province, as are populations and transportation networks.

As part of the Pacific Rim, British Columbia's transportation network provides a key link between North America and Asia and facilitates the movement of people and goods to support provincial, national, and international trade. In this context, British Columbia requires aviation, marine, road, and rail infrastructure that is resilient, effective, and efficient. While infrastructure in British Columbia is designed to withstand certain types of weather and climate conditions, building and maintaining a viable transportation system in the context of projected changes in climate – including temperature, precipitation, patterns of extreme weather, and other variables – is essential. Transportation systems in the province demonstrate vulnerability to both extreme weather events and incremental changes in climate conditions. While difficulties persist in identifying the location and criticality of infrastructure vulnerabilities and communicating them to decision-makers, progress is evident in advancing climate adaptation broadly.

This chapter examines the interactions and vulnerabilities of transportation infrastructure and operations to changes in weather and climate in British Columbia. It has a strong focus on engineering approaches to climate adaptation in the transportation sector. The science and practice of adaptation is a relatively new undertaking in the engineering field, with the consideration of future climate conditions remaining a challenge and new way of thinking for engineering professionals (see Box).

ADAPTING ENGINEERING PRACTICES TO CLIMATE CHANGE

While engineers have long considered climate related parameters in engineering design work, this has usually meant looking back at historic trends. Given the current rate of climate change, this is no longer a reliable approach. Provincial Professional Engineering Associations are responding by adding new professional requirements to ensure that potential climate change impacts are taken into account in the design process for the service life expected of the infrastructure. This is a cultural change for agencies responsible for infrastructure, consultants carrying out engineering design work and clients commissioning the work. It is expected that future engineering work related to new infrastructure design and rehabilitation will reflect such action and progress.

Due to the newness of this field and current limitations of climate models in providing information to engineering designers, many questions cannot yet be answered. For example, a particular climate parameter like extreme wind will have a significant effect on the future functionality and safety of a bridge being designed today. Anticipating how this parameter may behave 75 years from now is a level of uncertainty most engineering designers have not had to deal with before.

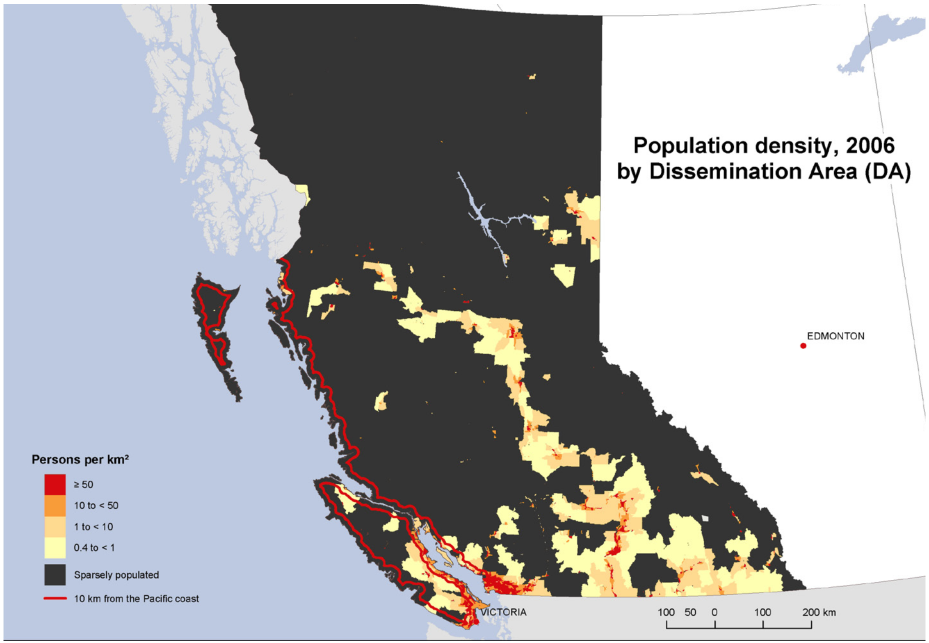
It will take time for engineers to develop procedures and processes to adequately deal with climate change, and maximize the likelihood that infrastructure being constructed today remains safe and effective for public use for the whole of its design life.

1.1 POPULATION

As of October 2014, British Columbia had a population of 4.7 million (Government of British Columbia, 2015a). The population is growing and becoming more urban, with the greatest growth in Greater Vancouver (Government of British Columbia, 2015b). In 1981, 22% of British Columbia’s population resided in rural areas and by 2011 this had declined to 14% (Statistics Canada, 2011). While the total number of rural residents remained relatively constant over that period, at around 600,000, urban population grew from 2.1 million to 3.8 million.

Most of the province’s population is concentrated in southern coastal areas (Figure 1). The Capital City of Victoria on southern Vancouver Island has a population of 327,000, while Greater Vancouver on the southern mainland of the province has a population of 2.4 million and comprises almost 60% of the province’s population (Government of British Columbia, 2015b).

Figure 1: 2006 British Columbia Population Densities. The large population centres are located on the south coast, while mountainous and northern areas are very sparsely populated. (Source: Statistics Canada)



1.2 ECONOMY

In 2013, British Columbia had a Gross Domestic Product (GDP) of $215 billion, which represents about 13% of Canada's GDP (Statistics Canada, 2011). Historically, British Columbia's economic activity was based around natural resources including forestry, mining and fishing. While these sectors are still important, the service sector has grown in importance, now accounting for four out of five jobs. Key service sectors include: finance, insurance, real estate, transportation, retail and wholesale trade, tourism, education, and manufacturing.

British Columbia's economy depends heavily on trade, including international and interprovincial imports and exports (Table 1). Trade within the Asian Pacific region has increased significantly since 2001. With the growth of China as a global manufacturing centre, demand for British Columbia's natural resources has increased. In 2011 British Columbia exported more to the Pacific Rim than to the United States.

Increased demand from China and India have challenged British Columbia's transportation infrastructure to meet these emerging opportunities. This infrastructure has played a key role in international trade due to its strategic location. For example, Prince Rupert, Canada's closest port to the Asia Pacific Rim, saves up to 68 hours of shipping time compared to locations to the south, such as Long Beach in Los Angeles (Port of Prince Rupert, 2014).

Table 1: International and interprovincial trade in British Columbia in 2013. (Source: Statistics Canada, 2015a)

Trade Element		Value	Percentage of Provincial GDP
Exports	International	$49.2 billion	23%
	Interprovincial	$35.7 billion	17%
Imports	International	$57.8 billion	27%
	Interprovincial	$41.8 billion	19%

1.3 GEOGRAPHY

British Columbia's unique landscape strongly influences the province's transportation systems (Figure 2). Ground transportation routes generally follow river routes and mountain passes, rather than the straight-line alignments typical of many other areas of Canada. Thus, routes can be circuitous and often involve significant changes in elevation.

British Columbia includes ten ecoprovinces, defined as part of a provincial ecoregion classification system (Figure 3). Ecoprovinces are areas with consistent climate processes, oceanography, relief and regional landforms. Each has a unique climate and they exhibit different sensitivities to projected climate changes. The ecoprovinces generally align with the physiographic features of the province, as do the major transportation corridors. With this understanding, it is possible to evaluate how climate change trends in British Columbia may affect transportation systems based on generalized climate change projections for relevant ecoprovinces within the province.

Figure 2: Physiological features of British Columbia. (Source: Encyclopedia of British Columbia and KnowBC.com)

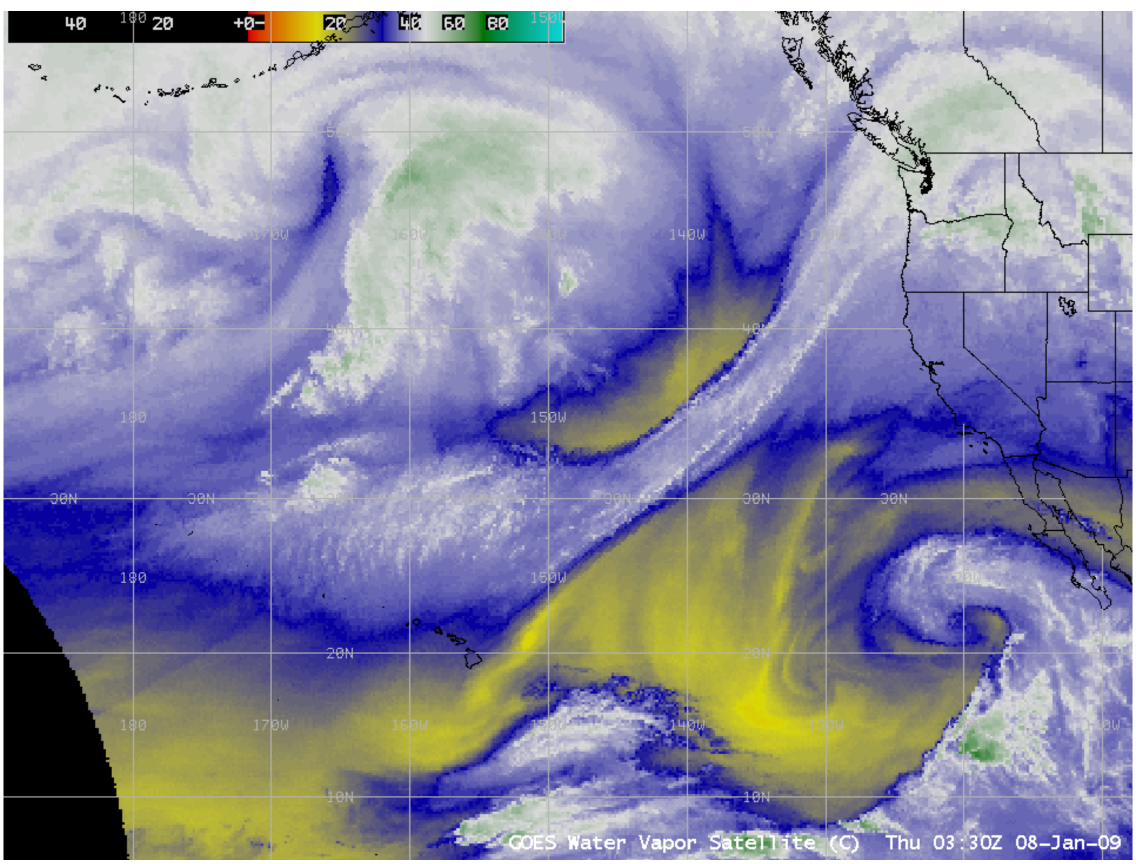
Figure 3: Ecoprovinces of British Columbia: Climatic zones of British Columbia. (Source: British Columbia Ministry of Transportation and Infrastructure)

2.0 CLIMATE

British Columbia's diverse landscape, including major mountain ranges, and proximity to the Pacific Ocean, strongly influence climate regimes in different parts of the province (Pacific Climate Impacts Consortium, 2013a). An important aspect of British Columbia's climate is a phenomenon known as "atmospheric rivers" that are associated with very heavy precipitation, and have had significant impacts on transportation systems. Atmospheric rivers are long narrow streams of high water vapour concentrations in the atmosphere that move moisture from tropical regions towards the poles across the mid latitudes. Pineapple Express is a term used to characterize an atmospheric river with origins in the western Pacific, east of Hawaii, flowing to and affecting the West Coast of North America between British Columbia and California (Figure 4). Atmospheric rivers are typically several hundred kilometers wide and thousands of kilometers long, and contain between 3 cm and 6 cm of water vapour in the middle of the stream (Pacific Climate Impacts Consortium, 2013a).

Atmospheric rivers occur most frequently in the fall and winter in British Columbia. Their impacts are greatest on coastal areas when the moist water vapor laden air rises over the Coast Mountains, resulting in intense precipitation. The impacts have been significant, for example, the January 2009 extreme event shown in Figure 4 lasted two days and cost nearly $16 million, while another two-day event in June 2011 resulted in flooding and cost more than $85 million. In 2012, 15 registered flooding events affected over 100 communities in British Columbia (Pacific Climate Impacts Consortium, 2013a).

Figure 4: Atmospheric River striking British Columbia on January 8, 2009. The colours in the image below represent "water vapour" in the middle to upper layers of the atmosphere. The shades of white to green are moist to cloudy and the shades of blue to yellow indicate increasingly dry areas. (Source: Cooperative Institute for Meteorological Satellite Studies / University of Wisconsin – Madison)



2.1 OBSERVED TRENDS

The Pacific Climate Impacts Consortium has done extensive work characterizing the current climate, identifying trends, and projecting future climate conditions for many regions in British Columbia. These reports provide an analysis of trends across the province for the period 1901 through 2009 (Table 2). Over this period, British Columbia has experienced shifts in both temperature and precipitation. These trends have accelerated since the 1950s. Overall, temperature across the province has increased by 0.18 °C per decade since 1951, an overall increase of 1°C. At the same time, the province has experienced generally wetter spring, summer, and autumn periods and significantly drier winters.

Table 2: Temperature and precipitation trends in British Columbia by ecoprovince. (Source: Pacific Climate Impacts Consortium, 2013b)

Ecoprovince	Temperature Trends (°C per Decade)		Precipitation Trends (mm/season per Decade)			
	1901–2009	1951–2009	1901–2009		1951–2009	
			SSA	W	SSA	W
Central Interior	0.13	0.20	3	3	3.7	-3
Southern Interior Mountains	0.12	0.16	5	4	7.7	-12
Taiga Plains/Boreal Plains	0.22	0.25	3.3	2	2.3	-1
Sub Boreal Interior	0.19	0.25	3.7	3	3.3	-3
Northern Boreal Mountains	0.16	0.21	3	4	2.3	-5
Georgia Depression	0.12	0.20	4.7	6	5	-13
Southern Interior	0.12	0.21	4.3	3	6.7	-6
Coast and Mountains	0.13	0.18	3	8	8	-6
Provincial Average	0.13	0.18	3.33	3.67	4.33	-5.44

SSA = Spring, Summer, Autumn
W = Winter

Relative sea level (relative to land height), has also been changing in British Columbia, with significant variability across coastal areas. For example, during the past 50 years, sea level rose by 3.1 cm at Victoria and 2.0 cm at Vancouver, but decreased by 8.4 cm at Tofino (Vadeboncoeur, 2016). A number of factors contribute to changes in ocean levels, including atmospheric and oceanographic effects, such as storm surges and climate-variability cycles (e.g., Pacific decadal oscillation) (Vadeboncoeur, 2016). One of the dominant factors affecting relative sea-level change in British Columbia is vertical land motion, which can be attributed to a combination of tectonic activity (interactions of the Juan de Fuca and Pacific oceanic plates with the North American plate), glacial isostatic adjustment (the ongoing movement of land that was once covered by glaciers from the last ice age), and changes in ice-mass in the Coast Mountains and Gulf of Alaska (Vadeboncoeur, 2016). Other factors that contribute to regional variability in sea levels include the influence of melting glaciers on nearby ocean waters and ocean surface topography alterations due to changes to ocean currents (Vadeboncoeur, 2016).

In addition to posing a long-term threat of coastal flooding, sea-level rise increases the risk of storm-surge flooding. Deeper water increases the height and energy of waves. Extreme high water levels, which typically occur as storm surges are superimposed on high tides, can be particularly destructive to coastal infrastructure.

2.2 PROJECTED CHANGES

The Plan2Adapt tool (Pacific Climate Impacts Consortium, 2013c), developed by the Pacific Climate Impacts Consortium, provides generalized climate change projections for British Columbia for three time horizons as well as for each of the ecoprovince designations based on a standard set of climate model projections (Tables 3 and 4). Projections are broadly consistent with observed climate trends (see Section 2.1). Overall, the climate in British Columbia will shift over the next 80 years with upwards of 2.7 °C of annual warming, wetter winters, generally drier summers and significantly longer frost-free periods.

Table 3: Projected changes in selected climate variables for the province of British Columbia for three time periods – the 2020s, 2050s and 2080s. Projected changes are relative to the historic baseline 1961-1990. The ensemble median is a mid-point value, chosen from a set of 15 Global Climate Model (GCM) projections for each of A2 and B1. (Source: Pacific Climate Impacts Consortium, 2013c)

Climate Variable	Season	Projected Change from 1961-1990 Baseline Ensemble Median		
		2020s (2010-2039)	2050s (2040-2069)	2080s (2070-2099)
Mean Temperature	Annual	+1.0	+1.8 °C	+2.7 °C
Precipitation	Annual	+4%	+6%	+9%
	Summer	+0%	-1%	+0%
	Winter	+4%	+8%	+13%
Snowfall	Winter	-2%	-10%	-12%
	Spring	-30%	-58%	-70%
Frost-Free Days	Annual	+10 days	+20 days	+30 days

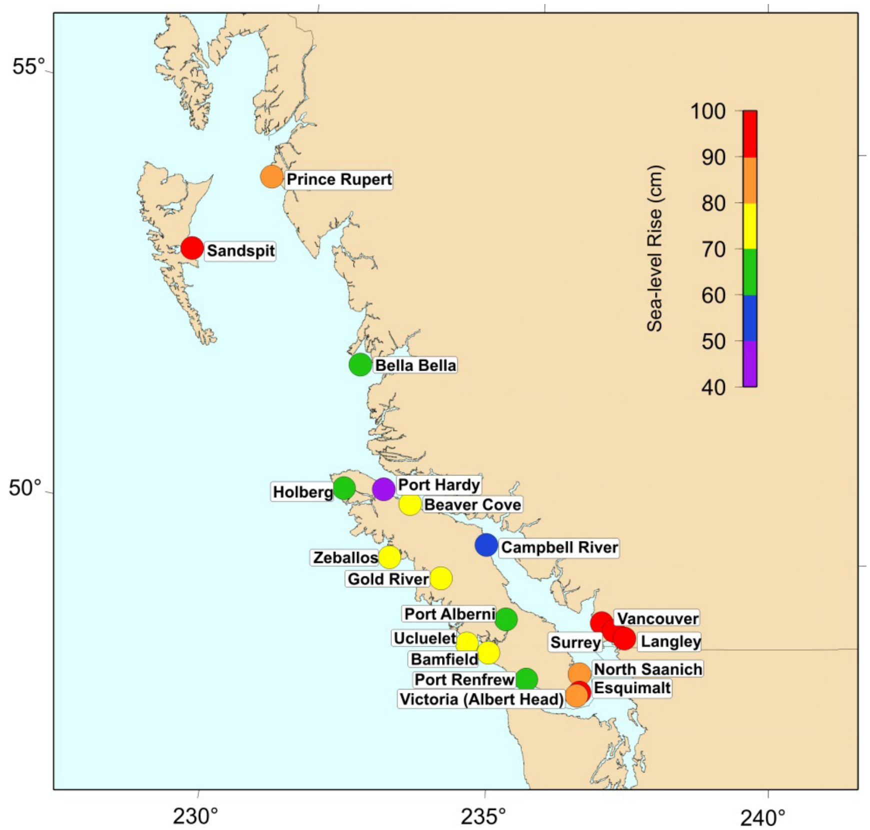
Table 4: Projected changes in selected climate variables by the 2080s for ecoprovinces in British Columbia. "+" denotes increase, "-" denotes decrease. (Source: Pacific Climate Impacts Consortium, 2013c)

Ecoprovince	Mean Annual Temperature Increase	Precipitation			Snowfall	Frost Free Days	Summary
		Annual	Summers	Winters			
Central Interior	+2.6	+	-	+	-74%	+35	Warmer, wetter winters Much drier summers
Southern Interior Mountains	+2.7	+	-	+	-69%	+34	Warmer, wetter winters Much drier summers
Taiga Plains	+3.0	+	+	+	-75%	+21	Warmer, wetter winters and summers
Boreal Plains	+2.8	+	No Change	+	-75%	+21	Warmer, wetter winters No change summer precipitation
Sub-Boreal Interior	+2.6	+	No Change	+	-75%	+30	Warmer, wetter winters No change summer precipitation
Georgia Depression	+2.6	+	-	+	-54%	+26	Warmer, wetter winters Drier summers
Southern Interior	+2.8	+	-	+	-75%	+37	Warmer, wetter winters Much drier summers
Coast and Mountains	+2.4	+	-	+	-71%	+35	Warmer, wetter winters Much drier summers

Climate change is not only associated with warming conditions, but also more extreme weather events such as high intensity rainfall (Murdock and Sobie, 2013). The Pacific Climate Impacts Consortium preliminary analysis indicates that the frequency of Pineapple Express events will increase by 2041-2070 with the largest increases on the coast. The average number of atmospheric river days per year is projected to approximately double at most locations, including the interior.

Projected changes in sea level in British Columbia (Figure 5) are similar to historic patterns (Section 2.1). The greatest amounts of sea level rise are projected to occur along the southern mainland and southeast Vancouver Island. The least amount of sea level rise is projected in areas where there is significant tectonic uplift, a non-climatic influence, described above in Section 2.1. Projections vary according to emissions scenarios, and changes in relative sea level could be negligible at some sites under a low emissions scenario.

Figure 5: Projections of relative sea-level rise for the year 2100 for the median value of the high emissions scenario (RCP8.5; *after* James et al., 2014; Atkinson et al., 2016). See Vadeboncoeur (2016) for additional information on sea-level projections. (Source: Natural Resources Canada)



3.0 OVERVIEW OF BRITISH COLUMBIA'S TRANSPORTATION SYSTEM

The British Columbia transportation system encompasses a variety of different modes, including roads and highways, rail, marine, air, and urban transit systems. The diverse hubs and networks related to these various modes act together to provide a cohesive transportation system that supports the people and economy of the Province of British Columbia, as illustrated in Figures 6 and 7. The alignment of the major transportation corridors and hubs along coastlines and within mountain passes and corridors is evident.

This chapter focuses on roads, rail, marine and air, with urban transit systems discussed in Chapter 9. While this chapter discusses each transportation mode individually, it is important to understand that they are heavily integrated. Weather impacts that adversely affect one mode of transportation can also have negative impacts on other modes.

3.1 ROADS

British Columbia has over 46,000 km of roads, including provincial highways (12,700 km) and side roads (33, 300 km) (British Columbia Ministry of Transportation and Infrastructure, 2014e; Figure 7), in addition to other municipal and federal roads. There are also over 2,800 bridges within the road system (British Columbia Ministry of Transportation and Infrastructure, 2014e).

Figure 6: Principle transportation infrastructure in British Columbia, including permafrost zones.

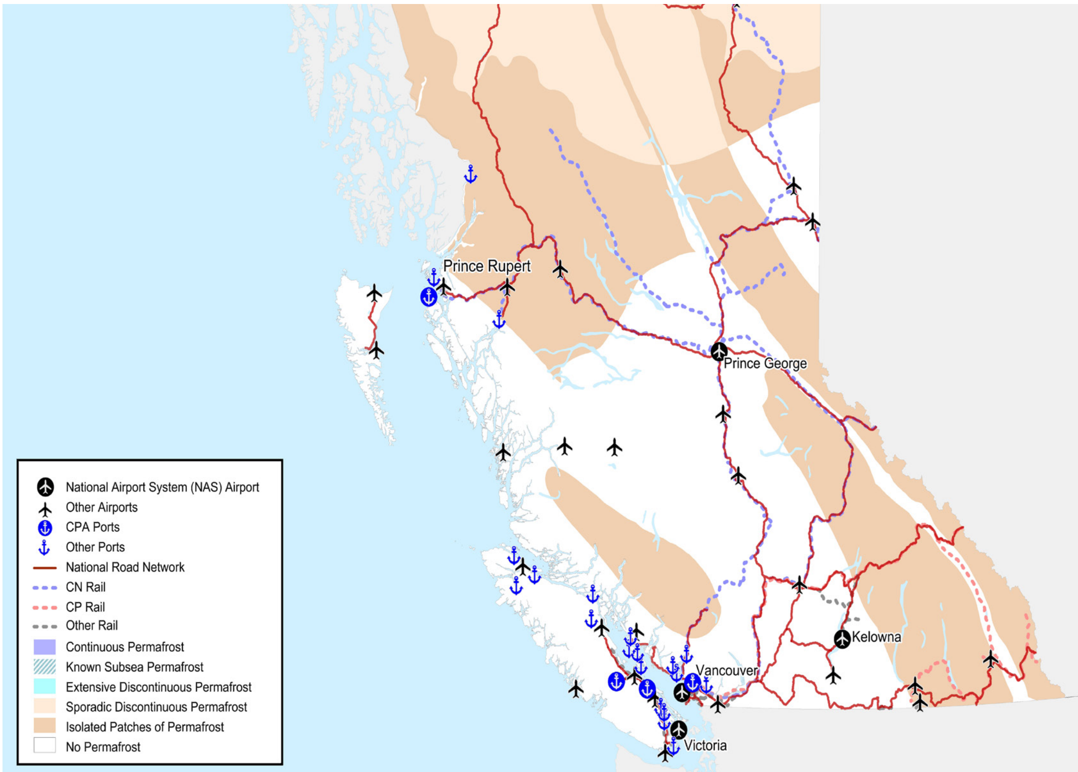
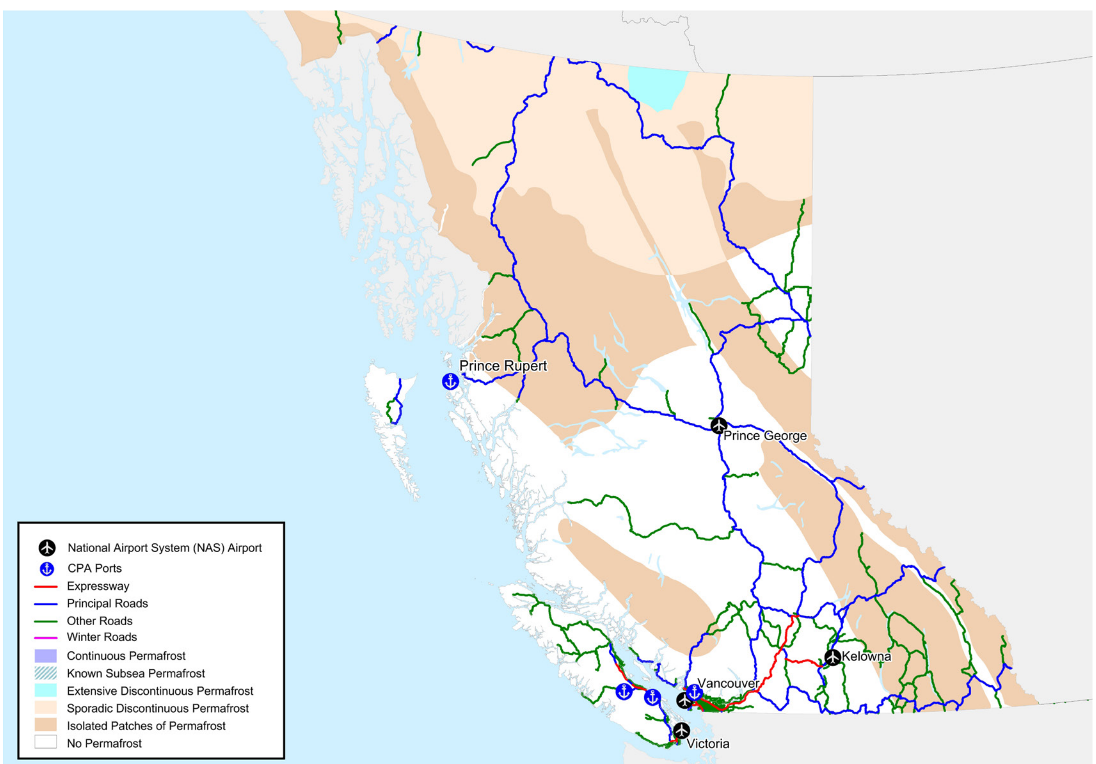


Figure 7: Road infrastructure in British Columbia.



In 2013, there were three million registered on-road vehicles in British Columbia, representing 13 percent of the Canadian total on-road vehicle registrations that year. This includes 2.7 million light-duty vehicles (automobiles, SUVs and lighter trucks), or approximately one vehicle for every 1.7 people in the province (Statistics Canada, 2015b). The province's population is, therefore, highly dependent upon the road system. Climate-induced interruptions in road service can have a significant impact on the lives and livelihood of the people of British Columbia.

3.2 RAIL

British Columbia has approximately 6,500 kilometers of railway (Figure 6), primarily served by Canadian National (CN) Rail (~4,400 km) and Canadian Pacific (CP) Rail (~1,720 km). Regional railways comprise another 402 km of track. This extensive infrastructure is designed to facilitate the efficient flow of goods through the Asia Pacific Gateway. The railways provide 24-hour, year-round service to port and terminal networks in Vancouver and Prince Rupert.

CN's main rail routes in British Columbia run from Vancouver to Edmonton, Alberta from Fort Nelson to Vancouver, and from Prince Rupert to Edmonton. CN Rail employs three Intermodal terminals in the province, located in Vancouver, Prince George, and Prince Rupert (CN, 2015). CN also operates an intermodal service from Prince Rupert, British Columbia to Whittier, Alaska. Called the AquaTrain, rail cars are loaded onto a barge directly and transported. Alaska is completely dependent on CN Rail AquaTrain service for its freight transport, as this service is connected to all Alaskan Freight train routes (Alaskarails, 2015). CP's main rail route runs from Vancouver to an Intermodal Terminal in Calgary, Alberta, and the company has one intermodal terminal in Vancouver (CP, 2015).

In 2013, the British Columbia rail system moved 63 million tonnes of commodities, representing over 20 percent of the Canadian total (Statistics Canada, 2015c). Of these, the principal commodities, by tonnage, were coal, lumber and wood products, sulphur, cement, automobiles, and wheat. Many of the commodities reflect the resource-based nature of the British Columbia economy, and indicate the impact of trade with the Pacific Rim.

In addition to freight services, VIA Rail offers passenger services along two corridors, from Toronto, Ontario to Vancouver (The Canadian) (Via Rail, 2015a) and from Jasper, Alberta to Prince Rupert, British Columbia (Western Canada) (Via Rail, 2015b).

3.3 AIR

There are 39 airports in British Columbia which are federally certified for passenger service, in addition to 251 registered land-based airports, aerodromes, heliports and water aerodromes (Transport Canada, 2015; Government of British Columbia, 2016a). Certified airports include Vancouver, the second busiest airport in Canada, Victoria the tenth busiest and Kelowna the eleventh busiest (Travel BC, 2016). (See Figure 6 for principle airports). Vancouver International Airport (YVR) handles over 19 million passengers and more than 256, 900 tonnes of cargo in 2014 (Vancouver Port Authority, 2014). Airport expansion plans are expected to increase capacity.

3.4 MARINE

British Columbia has three international ports, four regional ports, and 40 local ports (see Figure 6 for principle ports). Port Metro Vancouver is Canada's largest and busiest marine port, representing trade in excess of $187 billion annually with more than 160 countries (Port Metro Vancouver, 2014), and adding approximately $10.5 billion to the national economy (Government of British Columbia, 2011a). The three container ports in Vancouver, Prince Rupert and Nanaimo are interconnected with rail and road systems, as are major ports at Kitimat and Squamish. The ports of Stewart, Port Alberi, and Victoria have only road connections. Prince Rupert is the terminus of the Pacific Gateway Northern Corridor with capacity of 750,000 TEUs – container shipments are measured in 20-foot equivalent units, or TEUs, which represent one standard-sized shipping container (Government of British Columbia, 2011b; World Bank Group, 2016)). Vancouver is the terminus of the Pacific Gateway Southern Corridor handling upwards of 2.9 million TEUs of container traffic annually (Port Metro Vancouver, 2015a).

In 2010, the province's marine ports handled:

- 85 million tonnes of cargo traffic; and
- 2.86 million TEUs of container traffic *(Government of British Columbia, 2011c)*.

Principal exports, by tonnage were coal, forest products, grain, potash, petroleum products, and metals, minerals, and chemicals. Principal imports included: automobiles, household goods, construction materials, machinery, produce, base metals, and beverages. British Columbia's marine ports also handle a significant volume of passenger traffic. For example, in 2014 the Port of Vancouver handled 812,000 cruise ship passengers (Port Metro Vancouver, 2015b).

Ferries are another key element of the province's marine transportation system. 7.7 million vehicles were transported by ferry through the province's ferry system in 2014, representing 19.8 million passengers on 171,000 sailings (British Columbia Ferry Services Inc., 2015). BC Ferries, formerly a crown corporation and now a commercial organization, has 35 vessels and 47 ports of call providing passenger and cargo services to coastal locations in British Columbia. Ferry connections to the United States from British Columbia include the Alaska Marine Highway System, providing transport between Prince Rupert and South East Alaska. In the South, vessels between British Columbia and Washington State provide service to coastal and island locations. Inland Ferries transport passengers and cargo across rivers and lakes on the mainland. Other vessels such as water taxis also provide transport to various locations.

The next section discusses historic climate impacts, future climate risks and adaptation practices as they relate to road, rail, air and marine transport in British Columbia. Discussion of historic impacts includes several case studies of specific climate events.

4.0 ROAD SYSTEMS

4.1 HISTORIC CLIMATE IMPACTS

British Columbia highways have exhibited clear vulnerability to extreme rain events that have caused road washouts, mudslide blockages and bridge closures. Heavy precipitation can cause flooding in rivers and creeks and may also trigger debris flows that can block roads, and clog culverts leading to road washouts. Debris can also accumulate at bridge structures, potentially leading to bridge failures. In some instances, these events can isolate communities from their principle lines of supply.

Three events, which all resulted in washouts of road infrastructure systems, are highlighted here to illustrate the climate sensitivities of British Columbia's highway infrastructure. The locations of these events have subsequently been the focus of detailed vulnerability assessments by the British Columbia Ministry of Transportation and Infrastructure (see Section 4.2).

BELLA COOLA - SEPTEMBER 2010

On September 25th and 26th, 2010 an intense frontal system stalled over the Central British Columbia coast, bringing heavy rainfall exceeding the 1-in-200 year rainfall of 200 mm (TranBC, 2016). The rainfall resulted in washouts and rock falls which, along with flooding, closed Highway 20 between Tatla Lake and Bella Coola (Figure 8). The route was impassable at 12 locations, as 12.5 kilometres of Highway were damaged, underwater or simply gone. The impact of the road closure on local communities was made worse by other consequences of the storm as residents depended on diesel to generate electricity for heat, water and other vital services. Highway access to Tatla Lake and Bella Coola was not fully restored for 17 days and resulted in transportation repair costs of $45 million.

Figure 8: Bella Coola: Highway 20 Flood Impacts – Sallompt Road bridge approach washout.
(Source: British Columbia Ministry of Transportation and Infrastructure)

PINE PASS - JUNE 2011

Fifteen sites along Highway 97 in the Pine Pass were damaged during a 1-in-100-year rainfall event on June 25th and 26th, 2011 (British Columbia Ministry of Transportation and Infrastructure, 2014a). Damages included road washouts and flooding (overtopping) of bridges (Figure 9). The storm affected the entire Peace Region of British Columbia, with major floods and washouts damaging more than 280 sites on about 140 roads. Road access, north of Prince George was closed, restricting tourist travel between British Columbia and Alaska. Transportation infrastructure repairs arising from this storm took through the summer of 2012 to complete and resulted in repair costs of $80 million.

Figure 9: Pine Pass: Highway 97 Flood Impacts – Blocked road access between Pine Pass and Chetwynd. (Source: British Columbia Ministry of Transportation and Infrastructure)

STEWART - SEPTEMBER 2011

In early September 2011, 333 mm of rain fell in the Stewart region of British Columbia, including 111 mm of rainfall in a single 24-hour period (Fraser Basin Council, 2015). The event caused significant flooding and resulted in road washouts and bridge failures, including a failure of the bridge at Bitter Creek (Figure 10). Washouts and the damage at this bridge closed 61.5 km of Highway 37A from Stewart to the Meziadin Junction with Highway 37. The bridge failure isolated the town of Stewart from the rest of British Columbia, stranding 117 tourists and vehicles. Tourists needed to be air-lifted to Prince Rupert while vehicles were shipped out of the region by barge. A temporary bridge was constructed by the British Columbia Ministry of Transportation and Infrastructure, which was later replaced by a permanent structure. Transportation damages arising from this storm event resulted in $7 million in response costs and $11 million in repair costs that continued through the summer of 2012 to complete.

Figure 10: Stewart: Highway 37A Flood Impacts – Bitter Creek bridge failure. (Source: British Columbia Ministry of Transportation and Infrastructure)

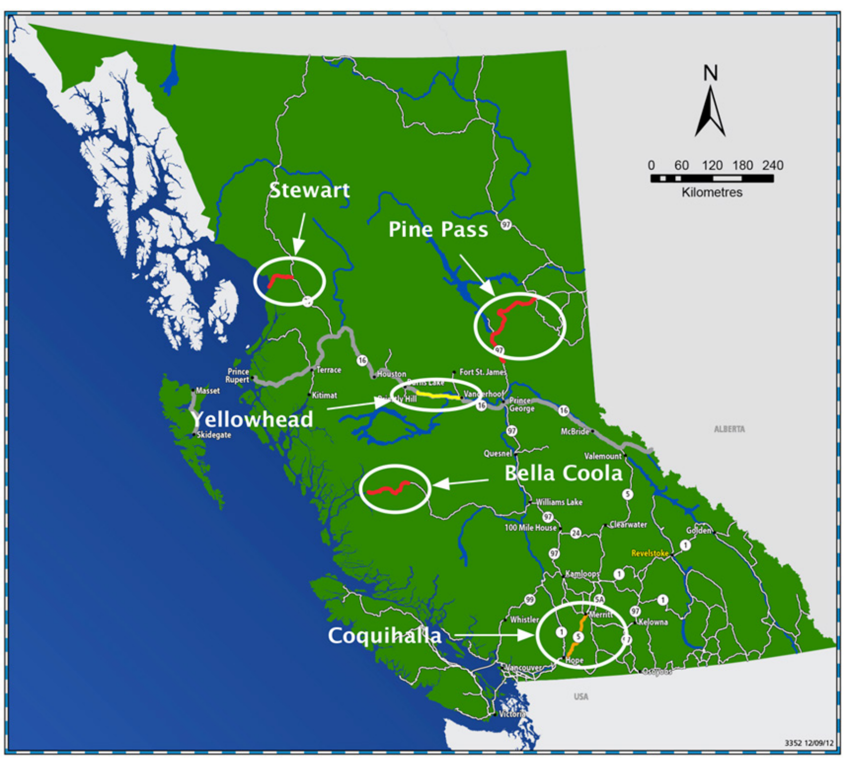
4.2 FUTURE CLIMATE RISKS

The British Columbia Ministry of Transportation and Infrastructure has completed five assessments using the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol (see Box) to determine vulnerability to road transportation infrastructure in British Columbia from future changes in climate, and identify potential adaptation measures (Table 5, Figure 11) (British Columbia Ministry of Transportation and Infrastructure, 2014b). The assessments covered a broad range of geographic and climatic conditions.

Table 5: British Columbia Ministry of Transportation and Infrastructure vulnerability assessments. (Source: British Columbia Ministry of Transportation and Infrastructure, 2014b)

Ecoprovince	Highway	Location	Date completed
Southern Interior	Coquihalla Highway (B.C. Highway 5)	Between Nicolum River and Dry Gulch	June 2010
Sub-Boreal Interior	Yellowhead Highway 16	Between Vanderhoof and Priestly Hill	April 2011
Coast and Mountains	Highway 20	Bella Coola region	Sept. 2013
Coast and Mountains	Highway 37A	Stewart region	Sept. 2013
Sub-Boreal Interior	Highway 97	Pine Pass Region	Sept. 2013

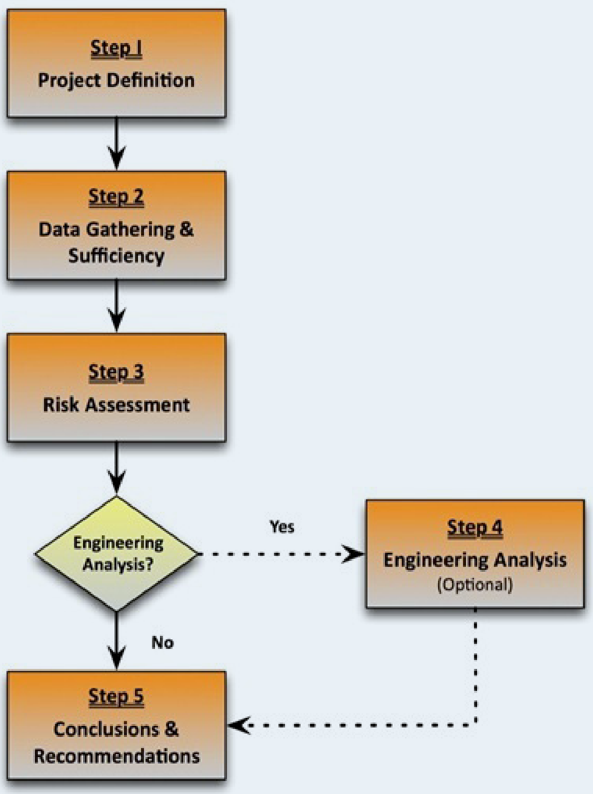
Figure 11: Locations of British Columbia Ministry of Transportation and Infrastructure Climate Change Vulnerability Assessments. (Source: British Columbia Ministry of Transportation and Infrastructure)



The **Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol**, led by Engineers Canada, was developed as a 5-step process to analyze the engineering vulnerability of individual infrastructure systems based on current climate and future climate projections (see Figure 12). Since 2012, the PIEVC Protocol has been applied to a wide variety of infrastructure types, including roads and airports.

For more information, see http://pievc.ca/

Figure 12: Engineers Canada PIEVC Protocol Process. (Source: Engineers Canada)



The Coquihalla and Yellowhead highway assessments considered a very broad range of infrastructure components and climate parameters, including:

- High and Low temperatures;
- Freeze / Thaw cycles;
- Frost / Frost Penetration;
- Rainfall - Total Annual; Extreme High; Sustained
- Snow Frequency; Snow Storm / Blizzard;
- Rain on Snow; Hail / Sleet; Rain on Frozen Ground;
- High Wind / Downburst;
- Rapid Snow Melt; Snow Driven Peak Flow Events (Freshet);
- Ice / Ice Jams; and
- Ground Freezing.

Results of these two assessments identified a common vulnerability - the impact of extreme rainfall, such as high-intensity, short-duration (HISD) rainfall events, on highway drainage infrastructure (see Box). This risk was more pronounced on the Coquihalla Highway study location, where the increasing future intensity and frequency of atmospheric river events was identified as a very significant vulnerability. A similar pattern of risk was identified for the Yellowhead Highway (British Columbia Ministry of Transportation and Infrastructure, 2014c).

As a result of these findings, and in consideration of recent extreme precipitation events in British Columbia that had damaged highway infrastructure, the remaining three highway assessments focused on extreme rainfall and other drainage challenging events.

CALCULATING EXTREME RAINFALL VALUES FOR INFRASTRUCTURE VULNERABILITY ASSESSMENTS

Extreme rainfall event design values are not always readily available for vulnerability assessments, especially for older infrastructure or through climate projection work. The values used for vulnerability assessments depend on the infrastructure system design, which in the past has relied on historical climate information for extreme events. They can vary significantly depending upon the location, topography, local and historical weather and climate conditions and the infrastructure involved. For example, the Coquihalla Highway assessment identified an extreme rainfall intensity event as >76 mm of rain over a period of 24 hours, while the Yellowhead Highway and highways 20, 37A and 97 assessments used 24 hour rainfall values of >35 mm and >98 mm, respectively, to define extreme rainfall. While the general projections outlined in Section 3 provide a starting point for this type of analysis, they are only the first step of a more focussed analysis necessary to answer questions about specific infrastructure systems.

Table 6: Summary of Findings from British Columbia Ministry of Transportation and Infrastructure Vulnerability Assessments. (Source: British Columbia Ministry of Transportation and Infrastructure, 2014b)

Vulnerability Assessment	Summary of Findings
Coquihalla	All high level vulnerabilities identified for this highway segment were associated with HISD events. HISD events also dominated the medium vulnerability outcomes.
Yellowhead	80% of the higher vulnerability items were related to HISD events. Other vulnerability factors identified included: • Bridge structure sensitivities to high temperature; • Sensitivity to freeze/thaw impacts on winter maintenance; and • Sensitivities to spring freshet impacts on culvert systems.
Bella Coola	Higher vulnerabilities were associated with the impact of freshet conditions on protection works and bridge end fill. Within the medium vulnerability category, 27% were related to HISD events. The remainder were associated with freshet events. These events are seen to challenge protection works, stabilization works and drainage elements in a very similar fashion to HISD events.
Stewart	Same results as Bella Coola; 26% of vulnerabilities related to HISD events.
Pine Pass	High vulnerabilities were associated with the impact of freshet conditions and HISD events on protection works and bridge end fill and third party utilities. Of the high vulnerabilities, five were directly related to HISD events while the others were associated with freshet conditions. Within the medium vulnerability category, 53% were related to HISD events. The rest were associated with freshet events. These events are seen to challenge protection works, stabilization works and drainage elements in a very similar fashion to HISD events.

All five highway segments examined also exhibited vulnerability to snowmelt driven peak flow events (freshet conditions). Such conditions generated risk profiles very similar to those associated with extreme precipitation – with generally increased risk of failure of drainage appliances, culverts and stabilization works (British Columbia Ministry of Transportation and Infrastructure, 2014b). These and other potential vulnerabilities identified through the assessments are listed in Table 6).

4.3 ADAPTATION PRACTICES

As a result of its climate change vulnerability studies, the provincial Ministry of Transportation and Infrastructure now requires infrastructure design work for the Ministry to include climate change implications. This includes a design criteria sheet where the designer indicates climate design baseline information, any additional climate change factors, and how the design will accommodate these climate changes over the infrastructure's service life. British Columbia is one of the first jurisdictions to require specific climate change adaptation measures to be included in infrastructure design work.

The Ministry of Transportation and Infrastructure also provides tools which can reduce safety risks to road users posed by extreme weather. Its DriveBC program aims to improve highway safety, by providing better real-time travel information for provincial highways on extreme weather conditions, road work, and closures. Since the program started in 2005, it has become the Ministry's most popular online tool (British Columbia Ministry of Transportation and Infrastructure, 2015).

5.0 RAIL TRANSPORT

5.1 HISTORIC CLIMATE IMPACTS

Severe weather conditions that affect freight rail services in British Columbia can significantly affect the transportation of goods in Canada and potentially international trade. The rail industry in British Columbia has a long history of managing the effects of weather conditions on its operations. A review of Transportation Safety Board of Canada (TSB) reports reveals an ongoing and evolving pattern of rail incidents associated with climate events, in particular high precipitation events in British Columbia's transportation corridors. The British Columbia rail system has experienced incidents related to extreme precipitation, spring runoff and drainage. These events can undermine railroad beds and are significant factors contributing to mud and rockslides that impact rail systems and equipment.

Three weather-related incidents, associated with varying degrees of infrastructure damage, environmental impacts and injuries to railroad personnel, are highlighted here and could be used as a foundation to evaluate the potential for climate change to exacerbate conditions that have historically led to interruptions in rail services. All three incidents arose from precipitation and drainage issues.

CONRAD – MARCH 1997

On March 26, 1997, a Canadian National (CN) train encountered a large roadbed depression near Conrad, British Columbia and derailed. The CN locomotive engineer and conductor were fatally injured, fourteen freight cars and two locomotives were damaged beyond repair and 1,200 feet of track and siding was destroyed (Figure 13). Leaking fuel ignited and resulted in a fire that made firefighting difficult and required helicopter water-bombing to contain.

Figure 13: Conrad, British Columbia train derailment. Collapse of the railroad subgrade was caused by extreme precipitation. (Source: Transportation Safety Board of Canada)

The investigation report for this incident provides extensive detail about the preceding weather conditions that led to this derailment (Transportation Safety Board of Canada, 1998). The key points from this analysis indicate that the period between October 1996 and March 1997 was the wettest six-month period in 59 years. March 26, 1997 was the 41st day of runoff from melting snow in the region. However, the rate of melting snow suddenly increased between March 17 and 19 when a rain on snow event occurred. The report concluded that the depression was caused by:

1. High seasonal runoff that was not managed by drainage systems above the adjacent Trans-Canada Highway; and
2. Water saturating the ground through the highway fills, infiltrating and destabilizing the railroad subgrade, which then collapsed.

KOMO – NOVEMBER 2009

On November 17, 2009, a Canadian Pacific (CP) freight train travelling west between Boston Bar and Vancouver struck a debris slide consisting of rock, mud and trees. The locomotive and three cars loaded with copper concentrate derailed (Figure 14). The locomotive engineer and conductor sustained non-life-threatening injuries. At the time of the incident, the area was experiencing very heavy rainfall, caused by an atmospheric river event.

The slide occurred during a period of heavy rain (Transportation Safety Board of Canada, 2010). Large volumes of water transited through a highway culvert located above the affected track. While the culvert had sufficient capacity to handle the water volume, diversion features downstream of the culvert were overtopped and significant volumes of water established an alternate channel that impacted the train tracks at a location where there were no culverts. The diversion resulted in rock, debris and mud being carried downslope and onto the track below.

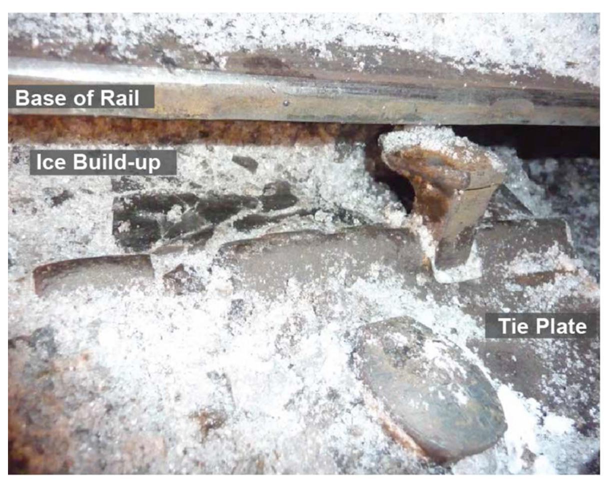
Figure 14: Komo, British Columbia train derailment caused by debris flow onto train tracks. (Source: Transportation Safety Board of Canada)

FERNIE – MARCH 2011

On March 8, 2011, twenty-seven rail cars loaded with coal derailed near Fernie, British Columbia. There were no injuries.

The TSB attributed the failure to rail rollover, resulting in excessive wide gauge (Transportation Safety Board of Canada, 2012). The rail gauge canted outward as a result of ice build-up between the base of the rail and the tie plates (Figure 15). The area had experienced numerous freeze-thaw cycles over the previous four weeks, which drew snowmelt water to the base of the rail through the pumping action of passing trains. The TSB report also notes *that between February 11 and 20, the ambient temperature was above 0°C during the day and below freezing at night. There were 23 millimetres of rain, between February 11 and 14, followed by snow accumulation of about 58 centimetres between February 15 and 17. After February 17, through the end of the month, the temperature was below freezing and as low as -32°C.* While this incident was attributed to freeze-thaw, the root cause was high levels of snow, contributing to snow-melt accumulation at the base of the tracks. This, combined with cycling between temperatures above and below the freezing point, contributed to the failure.

Figure 15: Fernie, British Columbia rail track showing ice build-up. (Source: Transportation Safety Board of Canada)



There are many other examples of incidents that demonstrate the sensitivity of rail transport in British Columbia to extreme precipitation. High-level summaries of ten other similar incidents over the period 1995 to 2009 are presented in Table 8.

Table 8: Summary of British Columbia rail incidents related to weather conditions (1995-2009).

Date	Location	Description	Citation
Jan 1995	Procter	• CP freight train struck fallen rock near Procter. Three locomotives and two cars derailed and fell 125 feet into Kootenay Lake. • Two fatalities due to drowning. • Sulphur and diesel fuel spilled into lake. • Attributed to pressure from tree roots, freeze/thaw cycles and surface runoff.	TSB Report No. R95V0017 Procter – Jan 20. 1995
May 1998	Creston	• CP freight train encountered roadbed depression, derailing three locomotives and eight gondola cars. • Silver/lead concentrate and diesel fuel were released, and later recovered. • Attributed to record rainfall, performance of drainage system, steep side hill slope and susceptibility of subgrade fill to water changes.	TSB Report No. R98V0100 Creston – May 31, 1998
Nov 2004	Ruby Creek	• CN train hit rockslide. • Fuel tank on locomotive ruptured resulting in fuel oil spill into Fraser River.	TSB Report No. R09V0235 Komo – Nov 17, 2009, Appendix A
Dec 2004	Glen Valley	• CN train stuck by mudslide. Eight cars derailed.	TSB Report No. R09V0235 Komo – Nov 17, 2009, Appendix A
Aug 2005	Lasha	• Landslide struck CN train. Nine cars derailed.	TSB Report No. R09V0235 Komo – Nov 17, 2009, Appendix A
Oct 2005	Yale	• CN freight train hit landslide. Two locomotives and seven flat cars derailed. Locomotive leaked fuel oil beside Fraser River. One crewmember sustained injuries requiring hospitalization.	TSB Report No. R09V0235 Komo – Nov 17, 2009, Appendix A
Jan 2006	Albion	• Two locomotives of a CP train derailed upright as a result of a landslide.	TSB Report No. R09V0235 Komo – Nov 17, 2009, , Appendix A
Jan 2007	Lasha	• CN train struck landslide derailing two locomotives and first car.	TSB Report No. R09V0235 Komo – Nov 17, 2009, Appendix A
Jan 2007	Inkitsaph	• CN train locomotive derailed upon striking landslide.	TSB Report No. R09V0235 Komo – Nov 17, 2009, Appendix A
Jul 2008	Lasha	• Four cars loaded with ethylene glycol derailed when struck by a mudslide.	TSB Report No. R09V0235 Komo – Nov 17, 2009, Appendix A

5.2 FUTURE CLIMATE RISKS

As rail corridors in British Columbia tightly parallel highway routing, with transportation corridors sharing mountain passes and routing along rivers, it is not uncommon for drainage failure events on one system to also negatively affect the other. In several of the case studies considered previously, failures on road system components resulted in mudslides onto the rail system. Therefore, severe weather events that negatively affect one system may have simultaneous impacts on others.

Climate change work by British Columbia's Ministry of Transportation and Infrastructure indicates that in these same corridors, highways will continue to be affected by intense precipitation events leading to drainage component failure and slope instability, and that these events are anticipated to increase both in frequency and intensity into the future. Given the close proximity between road and rail in British Columbia and the history of sequential and coincident failure of these systems, it is reasonable to project similar patterns of vulnerability for the rail system.

5.3 ADAPTATION PRACTICES

While specific references to rail companies conducting climate change assessment and adaptation work in British Columbia were not identified in the literature, it was observed that rail companies in British Columbia are making considerable effort to address the impacts of severe climate events, including extreme precipitation. The recommendations that arise from these investigations and follow up activities are very similar to those that may arise from focussed climate change assessment analyses. The forensic analysis conducted as part of the TSB investigation process is a critical input to climate change adaptation assessment, such as the work conducted by the British Columbia Ministry of Transportation Infrastructure for the province's highway system. Examples of these actions are listed in Table 9.

Table 9: Example follow-up actions from TSB Reports.

Date	Location	Follow Up	Citation
Jan 1995	Procter	CP: • Provided employees instruction on basic rock slope inspection, principles of rock slope stability, and methods for stabilization and protection; • Extended annual rock slope inspections; • Initiated aerial inspections to evaluate rock slope features at higher elevations; • Established a procedure to evaluate and catalogue a broader range of mitigative measures for rock slope instability.	TSB Report No. R95V0017 Procter – Jan 20. 1995
Mar 1997	Conrad	CN: • Constructed additional surface drainage works at Conrad, and installed a prototype washout detector; • Used aerial photographs to identify sites at Thompson/ Fraser geologically similar to Conrad; inspected those sites and installed drainage improvements; • Conducted geotechnical subsurface investigations at selected locations and installed instruments (pneumatic piezometers) to measure groundwater pressures; • Developed a slope-monitoring assessment procedure to report all incidents related to rockslides and landslides to the geotechnical department for action or for data to assess long-term stability of soil slopes.	TSB Report No. R97V0063 Conrad – Mar 26, 1997

Date	Location	Follow Up	Citation
May 1998	Creston	CP: • Provided training on rock and soil slope stability to track maintenance supervisors; • Initiated a new culvert inspection policy requiring that culvert inspections be carried out annually; • Contracted the services of World Weather Watch for a warning system to provide detailed, accurate weather forecasts, and notification of severe weather, referenced to track mileage and station; and • Instructed railway safety inspectors to focus on drainage issues and review railway maintenance practices in territories susceptible to slope instability.	TSB Report No. R98V0100 Creston – May 31, 1998
Nov 2009	Komo	CN and CP: • Monitor Fraser Canyon corridor and conduct regular inspections by geotechnical engineers/geologists; and • Engage in research to improve detection of rock falls and slides. CN: • Installed an Emergency Slope Washout System in the Komo area. • Implemented a protocol for local supervisors to contact CN and CP during rain events, periods of extraordinary runoff, and other potentially damaging weather systems and to notify railway contacts of any specific problems.	TSB Report No. R09V0235 Komo – Nov 17, 2009
Mar 2011	Fernie	CP: • Installed rolled tie plates and new rail at the derailment site; and • Moved the 30 mph speed sign to ensure that trains complete braking prior to reaching this curve, reducing the lateral loading on the curve. TSB: • Established a minimum frequency requirement for the electronic geometry inspection of all tracks.	TSB Report No. R11V0057 Fernie – Mar 8, 2011

Many of these sample actions are the type of recommendations that arise from focused vulnerability assessments. Actions cover a range of research, monitoring, procedural, maintenance, reporting and engineering activities. From this, we can conclude that rail companies in British Columbia are conducting activities to reduce climate risks (see Box). The TSB and rail companies extrapolate from forensic analyses of climate related failure events to establish generalized actions and approaches to mitigate the risk of such events throughout the rail system in general.

RAIL INDUSTRY APPROACH TO CLIMATE CHANGE (MICHAEL GULLO, RAILWAY ASSOCIATION OF CANADA, PERSONAL COMMUNICATION, 2015)

Railway capital investments address a variety of issues and challenges, including how extreme weather events such as flash flooding, avalanches, washouts, and freezing~~,~~ can lead to service disruptions within and around the railway network. To ensure the efficient movement of traffic, railways invest significantly in track infrastructure upgrades, execute seasonal readiness plans, test natural hazard warning systems, undertake regular rail inspections, and ensure processes are in place to mitigate against, and to recover from, severe weather situations. A variety of technologies are applied to determine the status of rail infrastructure and the landscape it traverses, including:

- Radar interferometer to measure track stability,
- Vulnerability assessment of risk area and GIS mapping,
- Landslide mapping; temporal and spatial,
- Geotechnical assessment of slopes,
- Laser movement detection system,
- Fiber optic detection for slope movement,
- River hydraulic studies; and,
- Beaver dam assessment and management.

For planning and operations, the rail sector generally uses short-term weather forecasts/ considerations, rather than long-term climate projections. Rail companies are concerned about climate change in terms of the potential for more frequent and/or intense severe weather phenomena, as these may cause catastrophic risk to the railway network and its operations. The Railway Association of Canada and the American Association of Railroads have both established Environment Committees that include extreme and inclement weather events within their mandates.

As with other transportation modes, the rail sector requires a scientific and fact-based approach to help them identify where climate change impacts are expected to occur in the short, medium and long term. With this knowledge, adaptation efforts within the sector can be targeted, and ultimately more strategic.

6.0 AIR TRANSPORT

6.1 HISTORICAL CLIMATE IMPACTS

Climate affects air transportation systems in many ways, including: 1) accidents where weather conditions have contributed to the causes; 2) service interruptions that have been caused by weather; and, 3) impacts on physical infrastructure systems.

WEATHER-RELATED ACCIDENTS

The air industry has a long history of managing and coping with weather conditions and has established standard procedures for accessing weather forecast information and incorporating that information into flight planning (Klock and Mullock, 2001). Impacts of severe weather are normally managed through avoidance practices, resulting in flight delays and through advancements in technology that incorporate advanced aircraft instrumentation systems. The result is a very low frequency of weather-related accidents.

In British Columbia, only seven aircraft incidents with weather related contributing factors over the last thirteen years have been of sufficient magnitude to warrant TSB investigation (Table 10).

Table 10: Summary of Aircraft Incidents Related to Weather Conditions.

Date	Incident	Contributing weather factors
Jun 6, 2002	Collision with Terrain, Needle Peak, BC (Transportation Safety Board of Canada, 2003)	Adverse weather in mountainous terrain
Jan 19, 2005	Control Difficulty Due to Airframe Icing, Kelowna, BC (Transportation Safety Board of Canada, 2005)	Severe in-flight icing conditions
Mar 8, 2006	Runway Overrun—Collision with Terrain, Powell River, BC (Transportation Safety Board of Canada, 2007)	Downwind conditions on approach; hydroplaning
Feb 7, 2008	Loss of Visual Reference / Collision with Terrain, Golden, BC (Transportation Safety Board of Canada, 2008)	Poor visibility
Mar 17, 2012	Runway Excursion, Blue River, BC (Transportation Safety Board of Canada, 2013c)	Deteriorating weather
Jun 1, 2012	Loss of Visual Reference and Collision with Terrain, Terrace, BC (Transportation Safety Board of Canada, 2013b)	Poor visibility
Aug 13, 2012	Collision with Terrain, Kelowna, BC (Transportation Safety Board of Canada, 2013a)	High-density altitude conditions and reduced visibility.

The TSB reports demonstrate that, historically, weather is rarely the sole cause of aircraft incidents. Rather, it is weather conditions and pilot error combined which led to an incident. Furthermore, the relative scarcity of weather-related aircraft incidents indicates that the air sector has effective, ongoing management strategies and technological development to accommodate severe weather conditions, and will not fly when conditions are unsafe.

WEATHER-RELATED SERVICE DISRUPTIONS

Weather-related delays and cancellations in air transportation services can be very disruptive to individuals and the Canadian economy, as they can have ripple effects across the national airport system. Causes include thunderstorms, fog, snow, and icing. In mountainous regions of the British Columbia interior weather-related fog and visibility issues can be problematic. Varying topography can result in very different weather conditions in close proximity. For example, the West Kootenay Regional Airport in Castlegar experiences frequent flight delays due to low ceilings and the surrounding mountains while the Trail Regional Airport, roughly 40 km south of Castlegar, offers better weather conditions and greater reliability in scheduled flights. Navigation technologies can play an important role in reducing weather-related delays. For example, the Northwest Regional Airport in Terrace, in the Coastal Mountains, often experiences weather conditions very similar to the West Kootenay Regional Airport, but has far fewer weather related cancellations. This can be attributed to Instrument Landing Systems (ILS) employed at the Terrace Airport that are not installed at West Kootenay. These systems can cost well in excess of $1 million to install, and are often considered uneconomic for smaller airports.

Changes in parameters affecting airport operations, and that can result in flight delays and cancellations, include extreme weather, storm surge and sea level rise over time. Fortunately airports in British Columbia can handle most snowstorm events, with the occasional service delay. Having appropriate snow removal equipment and staff can help to manage this type of event.

Visibility issues are more problematic. While Vancouver International Airport has an advanced ILS (enabling landing and departures in visibility conditions as low as 600 feet), not every airport in British Columbia is equipped with ILS. While other management options such as Required Navigation Performance may be available, they often require ongoing cooperation between regional airports and air carriers. The main approach to visibility issues is flight cancellation or diversion to alternative airports. This can inconvenience passengers, and over the long-term, potentially compromising regional growth.

IMPACTS ON PHYSICAL INFRASTRUCTURE SYSTEMS

Coastal airports may be exposed to the hazards of storm surge and sea level rise (see Box). For example, the low elevation of Vancouver International Airport's physical infrastructure could potentially be affected by storm surge and sea level rises over time. This airport is a major regional, national, and international hub, and disruption of service could have wide-ranging impacts on air mode reliability in British Columbia and elsewhere. The airport is located on Sea Island, close to sea level, and is also in the Fraser River floodplain where there is flooding potential from heavy precipitation affecting river flow, plus Pacific Ocean storm surge and changing conditions from sea level rise. A dyke system, approximately 15 km long, currently protects Sea Island. The Airport Authority has an ongoing program to manage the dykes and regularly assesses flood risk, while working in collaboration with federal, provincial, and local governments to define appropriate dyke elevations (Marion Town, Vancouver Airport Authority, personal communication, 2015). Other relevant measures at Vancouver Airport include ensuring the airport has an in-to-wind runway in virtually all wind conditions; and investments in pavement snow and ice control and de-icing, to ensure aircraft can safety operate in severe weather conditions.

SANDSPIT AIRPORT

Transportation infrastructure and operations at Sandspit Airport, Haida Gwaii, are susceptible to winter storms and associated storm surges with potential increases and attendant issues as sea levels rise over time. The runway is located across the 'spit' and heavy and frequent winter storms have caused severe wave damage to riprap revetment, which is a sloping structure made of rocks or other material, protecting the shore. Overtopping of the revetment has become more frequent in recent years, with damage and repairs occurring on an annual basis, including marine debris and driftwood on the runway and damage to airfield lights and pavement (Figure 16). The airport is also located within the Pacific Flyway, a route for migratory birds. Airport operators have observed changes over the last decade in migratory and resident birds that also affect management of the airport.

Figure 16: Sandspit runway from December 2011. The end of the runway was subject to severe wave overtopping during a significant storm event, with a sea surge approximately 1 metre above runway elevation. A 250 m section of damaged riprap needed to be re-constructed.

In light of these changes, the airport needs to continuously adapt its operations to ensure continued safety. The vulnerability of Sandspit Airport may need to be further assessed, along with new management approaches and practices, as the frequency and magnitude of storm surge events will increase as a result of sea level rise.

Written with input from Transport Canada staff, Pacific Region Office.

6.2 FUTURE CLIMATE RISKS

While visibility is an ongoing concern for British Columbia airports, it is presently unclear how climate change will affect the situation. The vulnerability assessments of highways by the British Columbia Ministry of Transportation and Infrastructure noted that current climate models cannot project changes in visibility conditions in the complex landscape of the British Columbia Interior Mountains. This issue has been identified by the Pacific Climate Impacts Consortium as a topic for further work, specifically to address transportation risks in the British Columbia interior.

Warmer and wetter winters in future might suggest a decline in snow-related air travel delays: however, projections of changes in the frequency and intensity of snowfall events over a shorter winter season remain uncertain. This represents another area where additional modeling work to assess the nature, form, frequency and intensity of future snowfall events for major British Columbia airports would be valuable.

Sea-level rise, and associated increases in storm-surge flooding, is a threat to operations at both Vancouver International Airport and Sandspit Airport (plus river flooding at Vancouver International Airport). As part of the Vancouver International Airport Authority's work to support the Airport Master Plan 2057, the Airport Authority is assessing climate change impacts on airport operations. The objective of this work will be to review and gain a better understanding of anticipated climate change impacts specific to Sea Island. Further work is expected to include the identification and quantification of possible risks associated with climate change impacts to airport operations. The results of these studies will culminate in adaptation plans from which any infrastructure improvements would be incorporated and funded through the Airport Authority's capital program.

6.3 ADAPTATION PRACTICES

The air sector manages weather conditions on an ongoing basis, adjusting practices as changes in weather phenomena are observed. In this sense, for many airports (with exceptions, such as Vancouver International Airport), adaptation tends to be primarily reactive, rather than performed in anticipation of future changes. At the same time, aircraft technology is evolving with more frequent use of instrument landing systems and other innovations allowing aircraft to fly safely in less than ideal conditions.

While there is very little information available regarding climate change risk assessment studies for air transportation in British Columbia, this does not mean that these studies are not being undertaken, as they may not be published or available in the public domain. For example, there has been a commitment to undertake a climate change risk assessment for the Vancouver International Airport that addresses risks of sea level rise and implications for the ongoing review and renewal of dike systems.

7.0 MARINE TRANSPORT

As a coastal province, and a major national hub for both passengers and goods, weather events that affect British Columbia marine transportation systems can have significant provincial and national impacts. As with aviation, impacts of concern include:

- Accidents where weather conditions have contributed to the causes;
- Service interruptions caused by weather; and,
- Impacts on physical infrastructure systems.

7.1 HISTORICAL CLIMATE IMPACTS

The marine sector has a long history of managing and coping with weather conditions and has established standard procedures for accessing weather forecast information and incorporating that information into voyage planning. As a result, impacts of severe weather are normally managed through avoidance practices (resulting in delays) and through improvements in technology that incorporate advanced weather monitoring and navigation systems. For example, Environment and Climate Change Canada maintains an extensive network of weather forecasting areas, observation sites and marine weather radio frequencies for the British Columbia coastline (Government of Canada, 2016). The system provides ongoing weather information to the marine sector and provides warnings of inclement weather that may affect marine transportation systems. This has resulted in weather-related marine accidents being relatively uncommon in British Columbia. A limited review of TSB reports suggests that any weather-related marine incidents involve strong components of human error.

Seaports in British Columbia must be able to handle high winds and heavy rainfall, normally at the same time. In 2014, four percent of British Columbia ferry sailings were delayed due to weather. High winds are a common cause of delays, with heavy rain another factor (British Columbia Ferry Services Inc., 2016). While the percentage is not large, it nonetheless represents 6,600 of the year's sailings being disrupted by weather conditions. Severe weather can not only result in delayed or canceled sailings, but can also affect physical infrastructure systems. For example, on November 3, 2015, high winds pushed the Queen of Nanaimo (ferry service between Vancouver Island and the Mainland) out of position, causing it to crash into and damage a private floating dock (CBC News, 2013). However, to date damage to physical infrastructure systems arising from weather related events has been relatively rare.

7.2 FUTURE CLIMATE RISKS

While wind is a key parameter in climate change forecast work, predicting the nature and intensity of short duration wind events is technically difficult and models are not good at simulating surface winds (Engineers Canada, 2008; Griffin et al., 2010). Specific studies aimed at assessing the impact of changes in high wind intensity and frequency on marine sector operations have not been identified. Existing practices that utilize a sophisticated network of weather monitoring and forecasting facilities may be sufficient to address future risks. Nonetheless, a changing climate may result in an increase in cancellations and delays, with economic implications. This is an area for further study.

Preliminary analysis (see Section 2.2) indicates a likely increase in the frequency of atmospheric river events by 2041-2070, with the largest increases on the coast. The average number of atmospheric river days per year is projected to approximately double at most locations, including the interior. Specific marine sector studies or activities to assess the impact of changing precipitation intensity and frequency on marine sector operations in British Columbia were not identified.

Studies are underway to examine flooding scenarios based on spring snow melt, coastal storm surge, king tides and sea level rise flooding for areas around the Fraser River, where a number of port facilities are located. These studies are being developed under a Lower Mainland Flood Management Strategy that involves a number of entities including municipal and provincial governments, the Fraser Basin Council and others such as Port Metro Vancouver (Kerr Wood Leidal, 2015). As part of this Strategy, the Fraser Basin Council is proposing to examine the vulnerability of key infrastructure, such as ports, rail, airports, highways, emergency or major road networks, and BC Hydro substations, to flooding.

Previously, the province completed studies assessing the impact of flooding from sea level rise and climate change on the Fraser River (Fraser Basin Council, 2014), and also published guidelines for the management of coastal flood hazard land use and sea dykes (Ausen Sandwell, 2011). As well, the British Columbia Professional Engineers and Geoscientists have published professional practice guidelines for flood assessments in a changing climate (Association of Professional Engineers and Geoscientists of British Columbia, 2012). The Ministry of Forests, Lands and Natural Resource Operations provides coastal flood hazard maps that indicate the impact of sea level rise for the entire provincial coastline for the year 2100 (Government of British Columbia, 2016b). The maps clearly indicate that by 2100, the region around Port of Vancouver will be a high flood hazard area, presenting risks to port infrastructure facilities that may disrupt the flow of goods and services into and out of the southern Pacific Gateway Corridor.

7.3 ADAPTATION PRACTICES

The extensive network of weather monitoring stations and forecasting services for the marine sector in British Columbia represents a primary response to reducing climate risks. The sector adjusts practices to accommodate inclement weather and may benefit from adjusting future practices to accommodate weather changes. The longer term risks to coastal infrastructure including ports, associated with sea-level rise are recognized by the provincial government. It has implemented a concrete plan of action that includes monitoring, and specific requirements for maintaining and upgrading sea dykes.

8.0 PROVINCIAL CLIMATE ADAPTATION PRACTICES

The Government of British Columbia has been working to better prepare the province to adapt to a changing climate. This includes a province-wide plan *Preparing for Climate Change: British Columbia's Adaptation Strategy*, which aims to build a foundation of knowledge and tools, make adaptation a part of the Government's decision-making, and assess risks and implement priority adaptation actions in key climate sensitive sectors (British Columbia Ministry of Environment, 2010).

Of specific relevance to transportation, British Columbia Ministry of Transportation and Infrastructure has developed a set of notional best practices based on the outcomes from their climate change vulnerability assessments of British Columbia highway systems (British Columbia Ministry of Transportation and Infrastructure, 2014e). These notional best practices are generally applicable to all transportation infrastructure systems, and are grouped into three primary categories: data, personnel; and, process (see Box).

BRITISH COLUMBIA MINISTRY OF TRANSPORTATION AND INFRASTRUCTURE - CLIMATE ADAPTATION PRACTICES

The notional best practices developed by the British Columbia Ministry of Transportation and Infrastructure include the specific practices identified below. To view the full best practices document, please visit: http://www.th.gov.bc.ca/climate_action/documents/MoTI-Climate%20Adaptation_Best%20Practices.pdf

Data

- Keep weather and climate data up to date
- Establish monitoring programs
- Always consider the impact of extreme precipitation events
- Consider combinations and sequences of events
- Identify sources for robust climate change information
- Ensure that projections are based on ensembles of climate model outputs

Personnel

- Strive for balance between computational methods and professional judgement
- Identify, monitor and manage climate change issues
- Establish multidisciplinary climate change review teams
- Work with qualified climate and meteorological professionals

Process

- Provide vulnerability assessment tools and appropriate training
- Use risk management to address uncertainties
- Incorporate climate change adaptation measures into planning cycles
- Mandate consideration of climate change in ongoing activities

9.0 INFORMATION AND KNOWLEDGE GAPS THAT CONSTRAIN DECISION-MAKING

This assessment has identified the following gaps in knowledge and information to advance adaptation decision-making related to transportation systems in British Columbia.

- **Extreme Precipitation Events.** Extreme precipitation events are the primary climate-related concern for road and rail transportation systems in British Columbia. Work is ongoing to characterize the future nature, frequency and intensity of such events. This work could be expanded with a focus on ensuring that decision makers have sufficient information and tools to inform system design, operation and maintenance for future extreme weather and climate conditions. Additionally, further work to characterize conditions that affect marine transportation and to project future precipitation event frequency and intensity would be useful.
- **Sea Level Rise Impacts on Coastal Infrastructure Systems.** Sea level rise and storm surge pose risks to coastal infrastructure in British Columbia, particularly to Vancouver International Airport, Sandspit Airport and Port Metro Vancouver. The Province of British Columbia has an active program to assess these risks and provide guidance to decision makers regarding adapting to sea level rise. Risk assessments will continue to be a key tool in ensuring that the owners and operators of critical coastal infrastructure facilities in British Columbia have the appropriate information to build, adjust and maintain infrastructure that is adaptable to sea level rise.
- **Marine Wind Events.** High winds can lead to sailing cancellations and delays within the marine transportation system. Climate change projections of high wind event frequency and intensity are not reliable. More work in this area would provide decision makers with a better foundation to plan and implement operational changes to adapt to changes in high wind event frequency and intensity.
- **Visibility Issues in the Interior.** Visibility can have significant impacts on road and airport operations in the British Columbia interior. While these issues are being managed, the causes of low visibility (fog) in the interior, and particularly the likely future changes in conditions that lead to these events, are not well understood. More knowledge about these weather effects could aid decision makers in implementing new systems and procedures to adapt to anticipated changes.

Climate change adaptation in all transportation marine modes in British Columbia has generally been reactive, with issues being addressed only after impacts have been observed. However, recent vulnerability assessments have examined longer-term climate change issues for some infrastructure. These studies of climate change and its effects on infrastructure will allow operators to better anticipate issues, and encourage the development of contingencies to adapt facilities, assets and operations to the risks posed by a changing climate. Given the contribution of rail, air and marine sectors to the provincial and national economies, additional climate change vulnerability assessments in all modes could be beneficial.

10.0 CONCLUSION

This chapter has demonstrated the vulnerability of British Columbia's transportation system to extreme weather and the changing climate, described practices to reduce these risks, and identified potential areas for additional work. The province's transportation network is critical for the effective movement of people and goods through airports, ports, rail, and roads – both within the province and between North America and Asia. However, many of British Columbia's transportation corridors, which traverse mountainous terrain and coastlines, are vulnerable to disruption and even failure resulting from climate events.

This chapter also indicates that infrastructure operators in British Columbia are primarily responding to failures, rather than anticipating and preparing for change. As a result, infrastructure impacts could be more severe than if proactive adaptive measures had been taken. Along with more robust data collection tools for climate and weather variables, and effective guidelines for data modeling and interpretation, proactive approaches (i.e. vulnerability assessments, infrastructure design requirements) could offer transportation decision-makers a stronger foundation for adaptive decisions. Sharing studies of climate vulnerability among operators and modes may improve learning and could benefit the transportation system as a whole.

The British Columbia Ministry of Transportation has assessed the vulnerability of several of the province's highways to climate change, and is one of the first jurisdictions to require that road infrastructure design work for the ministry consider climate change implications. This is an important indicator that adaptation efforts in British Columbia's transportation sector are advancing, though more work remains to be done.

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5 · Prairies

CHAPTER 5: THE PRAIRIES

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KEY FINDINGS:

- **Flooding associated with extreme precipitation events has been driving climate adaptation efforts for transportation in the Prairies, and increasing frequency and intensity of such events is a key future concern.** Flood-control strategies (e.g., expanded and enhanced culvert programs to reduce washouts, impermeable runway treatments) represent key adaptations for rail operations, airports (particularly in the northern Prairies), and roadways in the region to date.
- **The high variability inherent in the climate of the Prairies means that adaptation in the transportation sector is likely to involve both reactive and proactive measures.** Given climate uncertainties and cost challenges in the transportation sector, decision-makers in the Prairies tend to view operational adaptations on a case-by-case basis. The importance of long-term planning for infrastructure (including zoning requirements), however, is illustrated by damage sustained in recent flood events in southern Alberta and Manitoba.
- **Efforts are underway to address the vulnerability of winter roads to increasing temperatures in the Prairies.** While routing changes and technical adaptations have contributed to longer operating seasons in recent years, further projected warming may require more significant adaptations (i.e. the construction of all-weather roads).
- **Thawing of permafrost in the Hudson Bay Lowlands will continue to challenge the operational viability of rail in the region.** Since the track was laid in the 1930s, geotechnical engineers have made costly efforts to stabilize the rail bed. Over the long term, thawing permafrost is likely to increase stabilization challenges, although disappearing permafrost could also improve the viability of some techniques.

1.0 INTRODUCTION

A changing climate and extreme weather present both challenges and opportunities for Canada's Prairies, including the region's extensive transportation infrastructure and operations. One objective of this chapter is to identify what is known about the nature of climate impacts (both positive and negative) occurring now and in the future in Canada's three Prairie provinces – Manitoba, Saskatchewan, and Alberta. The chapter also aims to identify and describe efforts made by governments and transportation operators to adapt practices and improve infrastructure to enhance the resilience of the region's transportation network.

While referred to as "the Prairies" for simplicity in this chapter, the three provinces are quite distinct. The following section reviews some of the key geographic and economic characteristics of Alberta, Saskatchewan and Manitoba. More specific regional context is provided, where appropriate, throughout the chapter. Subsequent sections focus on climate impacts and associated adaptation practices for each major mode of transportation – roads, rail, aviation, and marine based on available information and practitioner experiences.

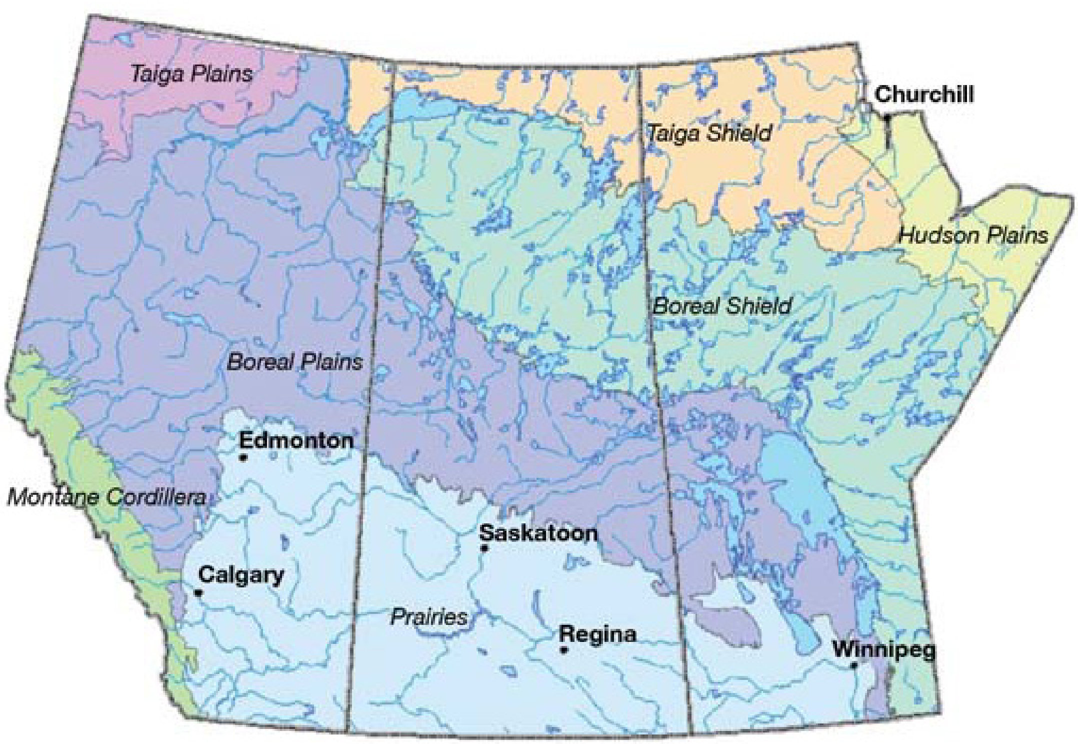
1.1 GEOGRAPHY AND THE PHYSICAL ENVIRONMENT

The Prairie provinces collectively account for approximately 20 percent of Canada's total surface area, including both land and water (Statistics Canada, 2005). The Prairies extend west from Hudson Bay to the crest of the Rocky Mountains, spanning several major watersheds and geographic areas (Sauchyn and Kulshreshtha, 2008). This results in significant climatic diversity (Figure 1).

The flat, dry plains of the south-central Prairie ecozone occupy 25 percent of the region's land area, characterized by persistent and often severe moisture deficits. This ecozone is the region's agricultural and industrial heartland, and one of Canada's most extensively-modified — only remnants of the grasslands and less than half of the wetlands that existed prior to European settlement remain (Sauchyn and Kulshreshtha, 2008). This region gives way to the Boreal Plains in central Manitoba, central Saskatchewan, and most of central and northern Alberta, an area characterized by mixed and coniferous forests (Sauchyn and Kulshreshtha, 2008). The Boreal Shield lies north and east of the interior plains in northern Saskatchewan and northeastern Manitoba.

The four remaining ecozones are on the margins of the Prairies, accounting for small proportions of the region's area and population. The Taiga Plains extend from the Mackenzie River valley of the Northwest Territories up the tributary valleys of northwestern Alberta, containing forests with limited productivity due to a cooler climate and shorter growing season (Sauchyn and Kulshreshtha, 2008). The Taiga Shield extends across Canada's subarctic, including the northern reaches of Manitoba and Saskatchewan and northeastern Alberta. At opposite corners of the Prairies are the Hudson Plains in the Prairies' northeast (containing the Hudson Bay Lowlands), which are dominated by extensive wetlands (Beaudoin et al., 1997), and the Montane Cordillera in southwestern Alberta. The Cordillera contains significant ecological diversity and landscapes of high relief, ranging from low-elevation fescue grassland through montane forest to subalpine forest and alpine tundra (Sauchyn and Kulshreshtha, 2008). Mountain snowpacks and glaciers of the Cordillera provide most of the southern Prairies' river flow and water supply (Sauchyn and Kulshreshtha, 2008).

Figure 1: Ecozones of the Prairie provinces. (Source: Natural Resources Canada)



All three provinces have temperate climates, with generally higher temperatures and precipitation levels in the south, although the Rocky Mountains create localized variations in climate. Altitudes generally rise east to west. Churchill, Manitoba, is located at sea level on the shore of Hudson Bay and represents the Prairies' only access to tidewater. Almost all road and rail infrastructure is concentrated in the Prairies ecozone, which also encompasses the region's five largest cities.

East of the Rocky Mountains, there are few physical limitations to surface transportation in the Prairies. The mountains constitute an evident barrier, although corridors through the Rockies have existed for many years. One of the most significant is Crowsnest Pass, which acts as a conduit for rail and roadways between Alberta and British Columbia (Babaian, 1985). Other major mountain routes include the Yellowhead, Kicking Horse, Howse, Athabasca, and Vermillion Passes. The potential for bottlenecks in these high-elevation passes represents one of the main surface transportation challenges in the Prairies.

Muskeg – "a living vegetative mat [overlying] peat in the presence of a very high water table" (Lautala et al., 2008) – in the Hudson Bay Lowlands presents another transportation challenge. Permafrost contributes to the terrain's low compressibility (Lautala et al., 2008). As a result, stable road and rail beds are difficult to maintain in these environments.

1.2 ECONOMY

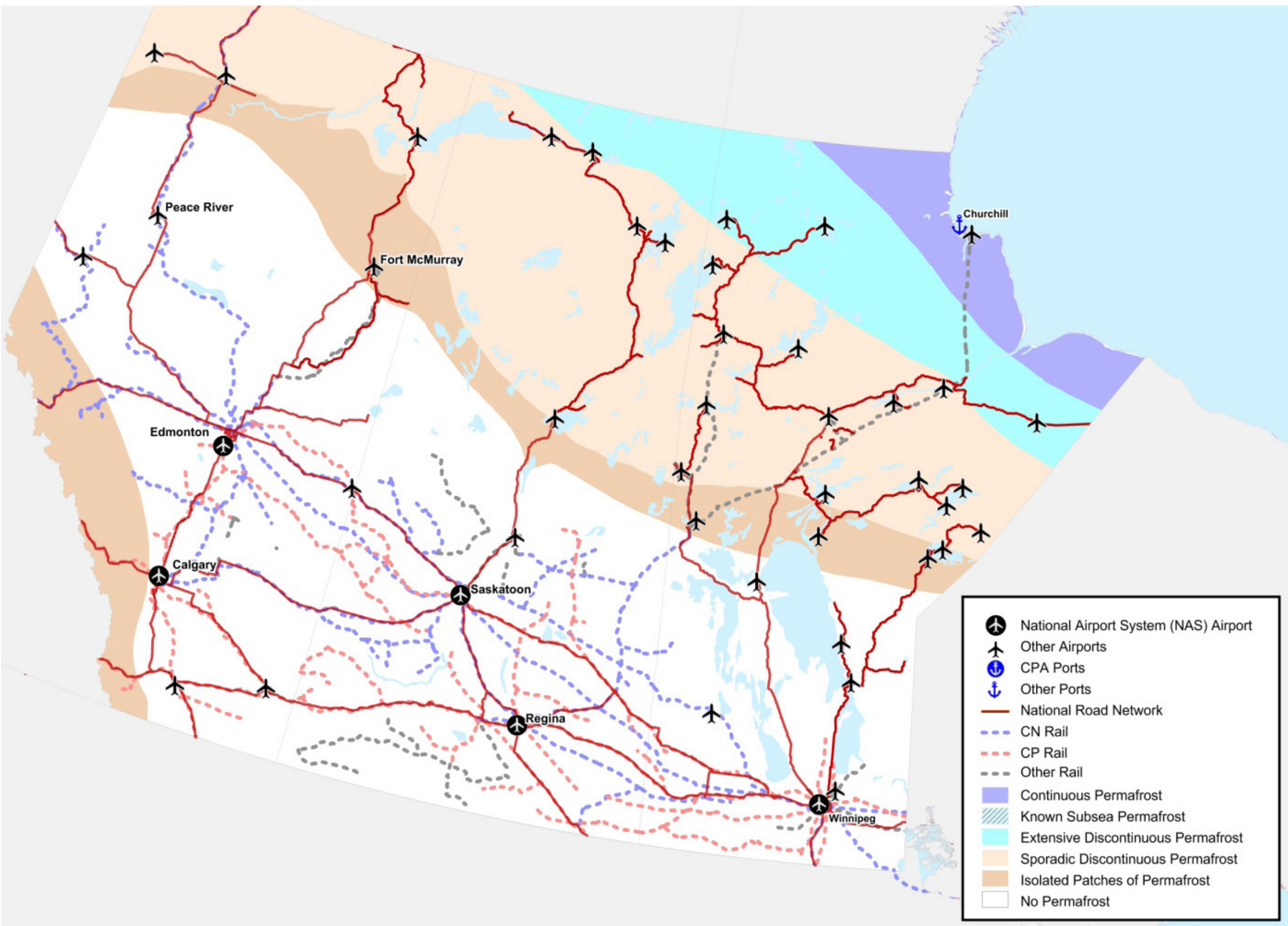
The Prairies economic strength derives from natural resource extraction. From 2010 to 2011, the gross domestic product (GDP) of the three provinces collectively rose 11.1 percent to $429.5 billion, nearly doubling the national growth rate. By 2014, the region's contribution to Canada's GDP totaled 25.6 percent. In 2014, Alberta contributed the largest share to the Prairies' combined GDP, due primarily to its extensive oil and gas reserves and large population. In 2013, Alberta contributed 72 percent of regional GDP, followed by Saskatchewan (14.7 percent), and Manitoba (13 percent) (Statistics Canada, 2014a).

The Prairies' share of GDP from transportation and warehousing remained stable from 2009 to 2013, ranging from 4.3 to 4.4 percent (Statistics Canada, 2014a). While the North American Industrial Classification System's transportation and warehousing designation represents the most direct measure of transportation's economic contributions, transportation indirectly enables many other forms of economic activity and growth (Ebert, 2000).

2.0 OVERVIEW OF TRANSPORTATION IN THE PRAIRIES

The Prairies' transportation network is extensive, with road, rail, and aviation providing options for the movement of people and freight. While the Prairies' surface transportation network supports significant marine activity in other Canadian regions, marine transportation plays a smaller role in the Prairies. Canada's only Arctic port is located at Churchill, Manitoba. In 2016, due to reductions in the volume of grain being moved through the port, the owner of the Port of Churchill, OmniTRAX, announced the closure of the port for grain shipments. Currently, the port remains open for resupply to Nunavut. Figure 2 presents a visual overview of major transportation infrastructure in the Prairies.

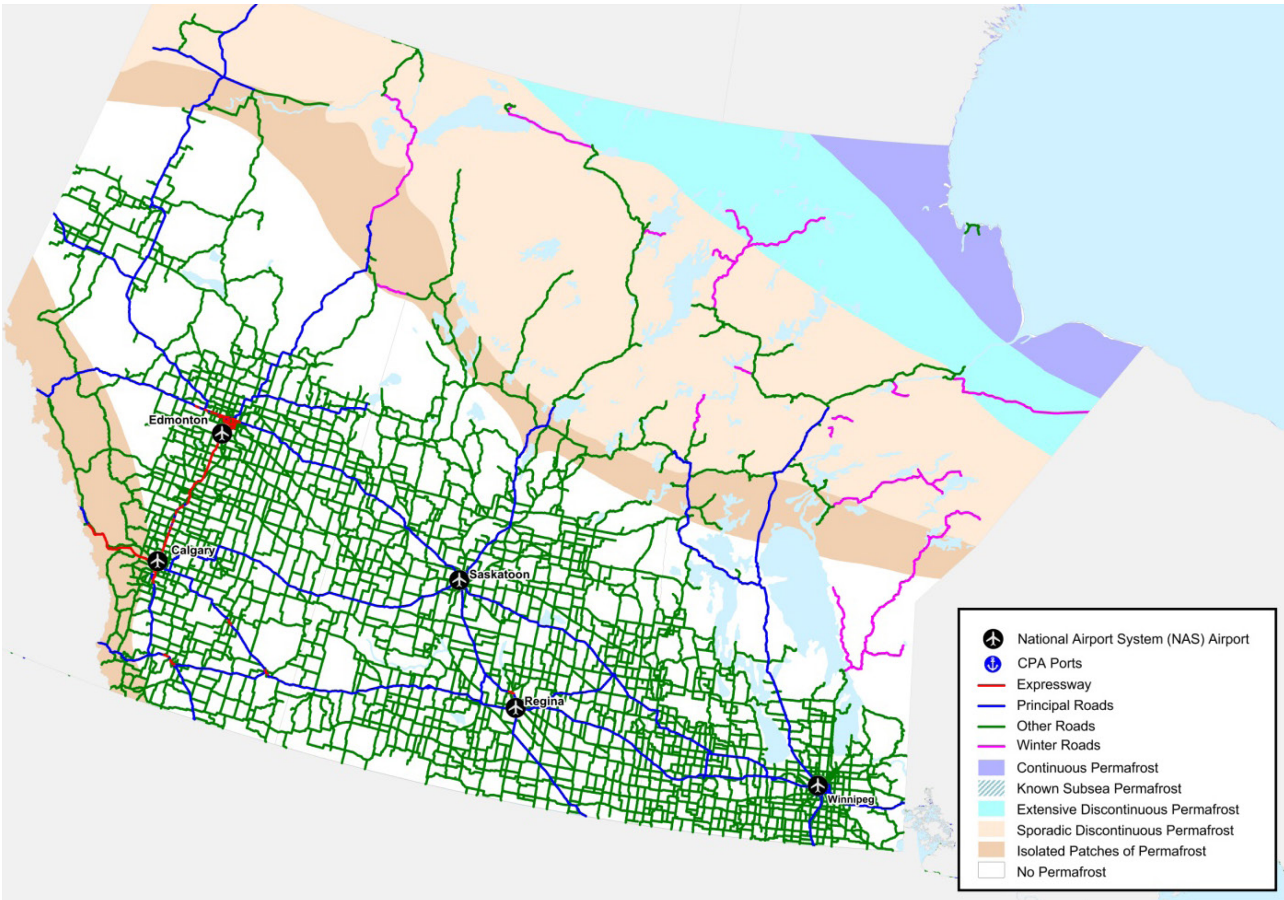
Figure 2: Principle transportation infrastructure in the Prairies, including permafrost zones. Note that the National Road Network depicted in this figure includes winter roads.



2.1 ROAD TRANSPORTATION

The Prairies have a relatively high number of road-km per capita due to an extensive municipal and provincial road network, and a lower population density than the national average (3.3 versus 3.7 persons per km^2) (Statistics Canada, 2011). The Prairies account for 47 percent of Canada's public roads, although this drops to 26 percent if only paved roads are considered (Transport Canada, 2015). Saskatchewan accounts for almost half (48 percent) of the region's total road-km (295,100 km), Alberta ranks second with 228,600 km (37 percent of Prairie road-km), followed by Manitoba, with 91,700 km (15 percent) (Transport Canada, 2015). Figure 3 demonstrates the extent of the Prairies' road network.

Figure 3: Road infrastructure in the Prairies.



There is significant trucking activity in the Prairies; much of this supports an extensive agricultural export market. Key road-freight border crossings in the Prairies include Emerson (Manitoba), Coutts (Alberta), and North Portal (Saskatchewan). These crossings collectively accounted for 12 percent of Canada's road trade with the United States in 2014, 9.2 percent of exports, and 14.2 percent of imports (Transport Canada, 2015).

2.1.1 WINTER ROADS

Winter roads (Figure 3) constitute an important part of the northern Prairies' road network, providing seasonal access to remote communities and reducing the tonnage of goods requiring more expensive air delivery. Winter roads enable the delivery of food, fuel, medical supplies, and building materials (reducing the costs of these goods); support local economies; and provide access to healthcare and other parts of the region.

Manitoba's winter roads typically operate from mid-January to mid-March, extend approximately 2,500 km, and serve 28 communities with a total population of 30,000 (Taylor and Perry, 2014). Comparably, winter roads in Alberta and Saskatchewan (with similar operating seasons) are modest: Alberta operates two routes totaling 447 km, while Saskatchewan's three winter roads cover 274 km (Federal/Provincial/Territorial Sub-working Group on Northern Transportation, 2015). There is significant concern that warmer winters associated with changing climate conditions will result in shorter operational seasons for freight operators; however, as discussed in Section 4.5 and Case study 3, recent years have witnessed longer seasons (Sauchyn and Kulshreshtha, 2008).

2.2 RAIL TRANSPORTATION

Rail transportation makes a significant contribution to freight movement in the Prairies. Three Class-I railways[3] (Canadian National - CN, Canadian Pacific - CP, and Burlington Northern and Santa Fe - BNSF) carry the vast majority of regional rail freight. Most tracks are located in areas without permafrost. One exception is the rail line connecting Churchill, Manitoba with supply-chain hubs to the south (Figure 2).

Although the operational length of Canada's rail network has declined in recent years, the Prairies have resisted this trend. As of 2012, the regional network had retained 94 percent of its 2008 length (Railway Association of Canada, 2015). In 2013:

- Alberta had 6,679 km, used by CN, CP, Great Sandhills Railway, Alberta Prairie Railway Excursions, Great Canadian Railtour Company, and VIA;
- Saskatchewan had 8,181 km, used by CN, CP, Carlton Trail, Great Western, Great Sandhills Railway, and VIA; and
- Manitoba operated 4,448 km, used by CN, CP, BNSF, Central Manitoba, Hudson Bay, and VIA.

In all three provinces, freight comprises approximately 98 percent of track usage (based upon fuel consumption), with passenger traffic accounting for the remainder. In 2009, 39 million tonnes of rail freight originated in Alberta, 27 million tonnes in Saskatchewan, and 10.6 million tonnes in Manitoba (Railway Association of Canada, 2015).

In 2013, three of Canada's top-ten freight-rail border crossings were located in the Prairies: Warroad, Minnesota-Sprague, Manitoba; Portal, North Dakota-North Portal, Saskatchewan; and Pembina, North Dakota-Emerson, Manitoba (Transport Canada, 2014).

2.3 AVIATION

Aviation is also an important mode of transport in the Prairies. There are five National Airport System airports in the region (serving Calgary, Edmonton, Saskatoon, Regina, and Winnipeg), which accounted for 22 percent (28.7 million) of Canada's total enplaned/deplaned passengers in 2014 (Transport Canada, 2015). Arrivals/departures at these airports accounted for 78 percent of the region's passenger movements in 2014.

Air freight is often chosen for higher-value shipments; therefore, air freight tends to account for a larger share of freight by value than by weight compared to other modes. Accounting for all inbound and outbound shipments in 2014 (both domestic and international), Manitoba moved 65,873 tonnes, Saskatchewan handled 12,077 tonnes, and Alberta accounted for 113,933 tonnes (Statistics Canada, 2014b). Principal airports in Manitoba are shown in Figure 2.

2.4 MARINE TRANSPORTATION

A review of marine transportation in the Prairies is essentially a review of the Port of Churchill in Manitoba (the Prairies' only access to tidewater). Opened in 1931, the Port is an artery to northern Manitoba and the central Arctic region (Government of Manitoba, 2015a). In 2016, the private owner of the port, OmniTRAX, announced the closure of the port for grain shipments, due to the limited volume of grain moving through the port. Currently the port remains open, supporting resupply to communities located in Nunavut.

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3 This refers to carriers with operating revenues exceeding $250 million (Railway Association of Canada, 2015).

Churchill is capable of handling Panamax-sized vessels with four berths totaling over 900m in length, although these facilities are modest compared to other Canadian ports. The Port of Churchill operates within (approximately) a 14-week shipping season, beginning in mid-July and extending to the end of October/early November. The shipping season is estimated to lengthen by two to three weeks over the 21st century in tandem with a shorter sea-ice season in the Hudson Strait (Hochheim and Barber, 2014), offering new opportunities for resource and resupply shipping (Lackenbauer and Lajeunesse, 2014). The seasonal duration of sea ice in this area has declined since record-keeping began in the 1970s (Tivy et al., 2007; Hochheim and Barber, 2014).

3.0 CLIMATE PROFILE

The Prairies are generally characterized by extreme differences in seasonal temperatures (an annual range of more than 70˚C), and high year-to-year variability in precipitation (resulting in frequent flooding and recurrent drought). Because of the region's mid-latitude location in the rain shadow of the Rocky Mountains, the climate is generally cold and sub-humid (Sauchyn and Kulshreshtha, 2008). The region's southern core has a sub-humid climate that becomes semi-arid during periods of drought (Lemmen et al., 1998). Water balance increases moving west, north, and east from this core area. Snow is a critical form of seasonal water storage throughout the region. Chinook winds, that can raise air temperatures by more than 20˚C and rapidly deplete snow cover, are a common winter phenomenon in the foothills and prairies of the southwest. Severe summer storms and lightning – often associated with damaging hail (Kovacs and Thistlethwaite, 2014) and, occasionally, tornadoes (Environment Canada, 2015a) – are key climate risks in the Prairies.

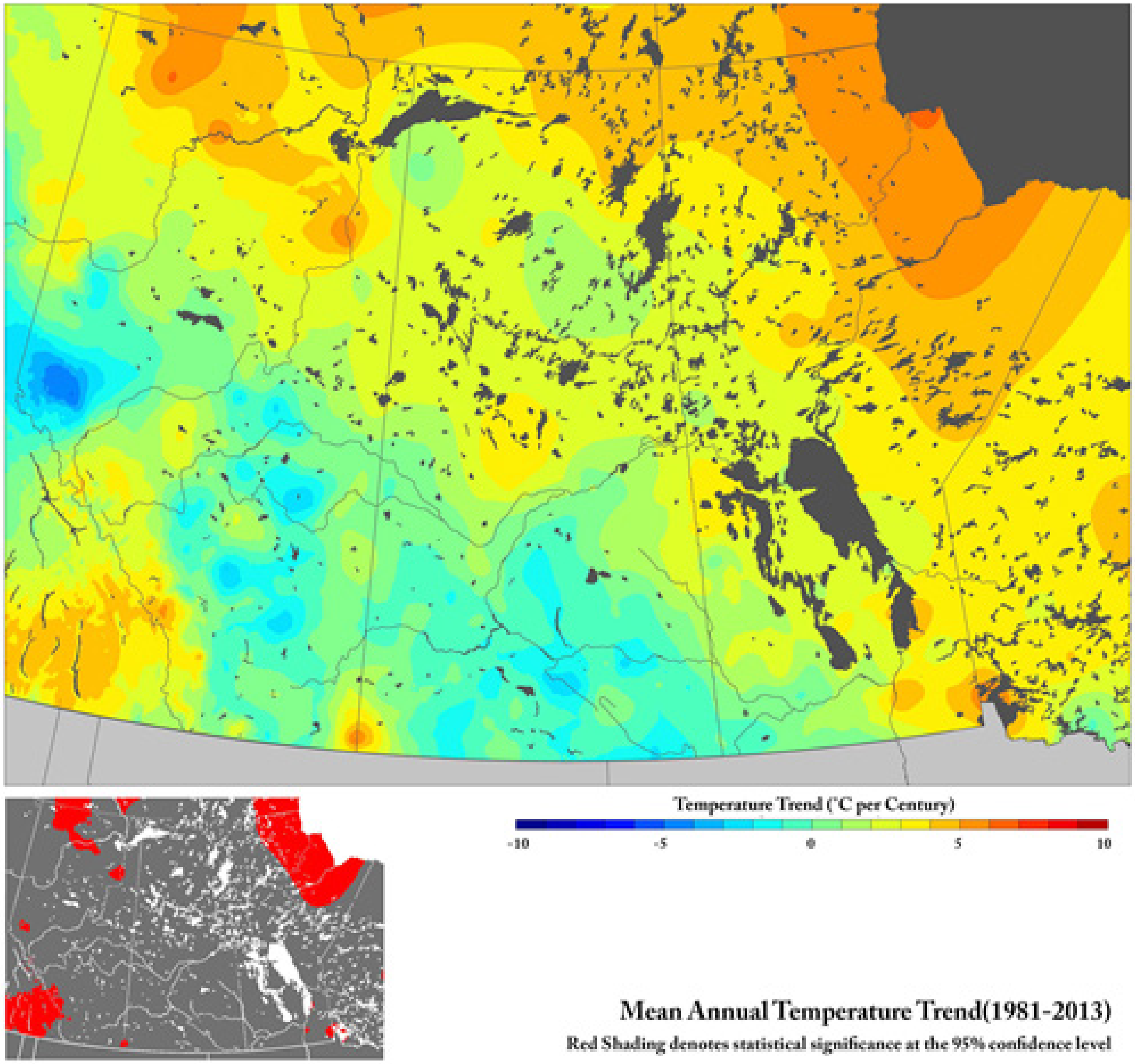
In the context of a changing climate, increasing water scarcity represents a risk to the region. Also, the Prairies are likely to lose advantages associated with cold winters, particularly as they relate to winter roads (Sauchyn and Kulshreshtha, 2008).

3.1 PAST TRENDS

Instrumental climate records on the Prairies extend more than 120 years. Despite high year-to-year variability, long-term records demonstrate increasing mean annual temperatures, ranging from 0.9˚C at Calgary, Alberta, to 2.7˚C in Swift Current, Saskatchewan for the period 1895-2005 (Sauchyn, 2010). For the period from 1948 to 2014, the warming trend in the southern Prairies was 1.5˚C, with northern areas experiencing even greater warming (approximately 1.8˚C) (Environment Canada, 2015b). This warming is similar to the average increase for Canada as a whole (1.6˚C) (Environment Canada, 2015b) and is about twice the increase in mean global temperature over the same period (Intergovernmental Panel on Climate Change, 2013). The greatest warming is evident in winter and spring, with the least occurring in fall (Vincent et al., 2012).

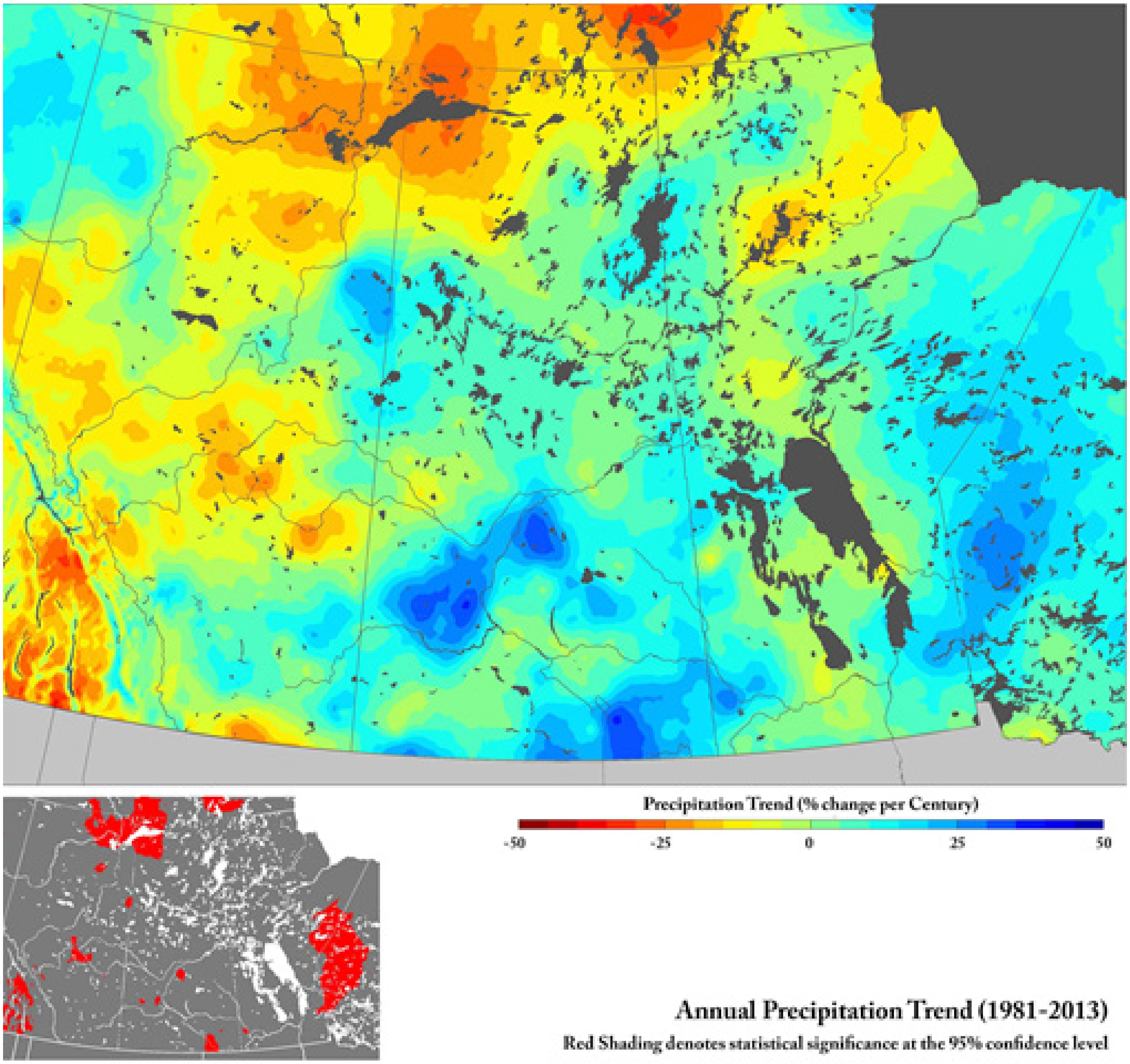
In addition to significant variability between and among years, there is also significant spatial variability across the region. In examining mean annual temperature trends, research (Danny Blair and Ryan Smith, University of Winnipeg, personal communication, 2015) demonstrates that most of the region experienced no statistically significant change (at a 95% confidence level) for the 32-year period from 1981 to 2013 (Figure 4). However, this indicates the importance of long-term records in defining climate trends. For the 60-year period from 1950 to 2010, Vincent et al. show statistically-significant increases in mean annual temperature for almost all sites in the Prairies, and no sites in the region show a cooling trend (Vincent et al., 2012; Bush et al., 2014).

Figure 4: Trends in mean annual temperature for the Prairie provinces for the period 1981 to 2013. Only areas in red on inset map show statistically significant changes. The scale bar depicts per-century trends. (Source: Danny Blair)



Trends in mean annual precipitation for the Prairies are much weaker than trends in mean annual temperature. This reflects, in part, the large differences in yearly precipitation, with the driest regions experiencing the largest inter-annual variability of any records in Canada (Sauchyn, 2010). Again, spatial variability is important (Figure 5). The 60-year record (1950-2010) shows statistically-significantly changes at only a handful of sites on the Prairies, and these show both increasing and decreasing precipitation (Bush et al., 2014).

Figure 5: Trends in mean annual precipitation for the Prairie provinces for the period 1981 to 2013. Only areas in red on the inset map show statistically-significant changes. The scale bar depicts per century trends. (Source: Danny Blair)



While trends in total precipitation remain poorly defined, the annual number of days experiencing precipitation has increased. Heavy precipitation events show no strong trend, with sites recording both increases and decreases in the number of heavy precipitation days for the period from 1950 to 2010 (Bush et al., 2014). Like other sites in southern Canada, the Prairies are experiencing a decrease in the snow-to-rain ratio (Mekis and Vincent, 2011). While no trend is evident in the frequency and severity of drought in the Prairies over the 20th century (Bonsal et al., 2011), global analysis shows a trend towards more severe drought conditions over Western Canada during the second half of the 20th century (Dai, 2011; Seneviratne et al., 2012).

Trends in extreme weather in the Prairies are also important. Research suggests that May-June precipitation over the southeastern Prairies has increased significantly since the 1990s, possibly explaining observed changes in runoff patterns and recent extreme flood events (e.g. 2011 and 2014) (Szeto et al., 2015).

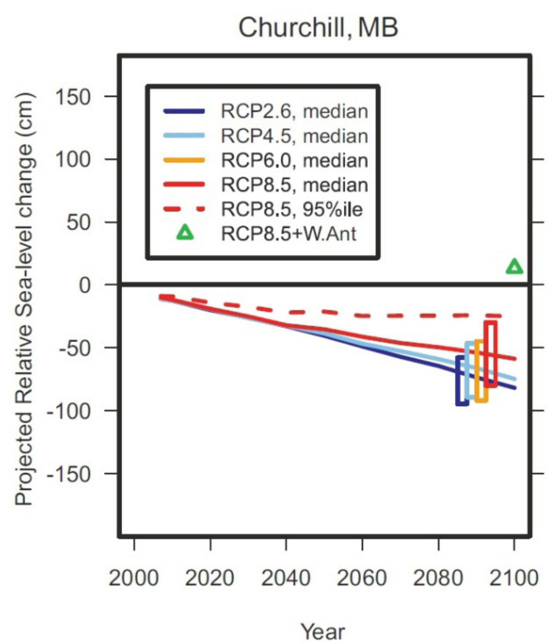
3.2 PROJECTIONS

Temperatures in the Prairies are projected to rise under all climate scenarios, with associated changes in evapotranspiration leading to increased aridity in many areas (Sauchyn and Kulshreshtha, 2008). Under a low-emissions scenario, warming will increase only slightly from historic trends; however, under a high-emissions scenario, increases exceeding 6˚C are possible this century (Bush et al., 2014). The greatest warming will continue to be experienced in winter, with the least occurring during summer.

Projections of precipitation changes show total precipitation increasing over the northern Prairies, with relatively minor changes projected for southern areas (Bush et al., 2014). Again changes are more significant under higher-emission scenarios. In the southwestern Prairies, decreases in summer precipitation are projected under high-emission scenarios. While the southern Prairies have been identified as a region with a higher likelihood of experiencing more frequent drought in future (Bonsal et al., 2013), there is no strong agreement between projections of various climate models (Bush et al., 2014). Instances of extreme rainfall are likely to increase in tandem with warmer temperatures, while instances of freezing rain are likely to increase while snow cover declines over the 21st century (Kharin and Zwiers, 2000; Bush et al., 2014).

Sea level changes are important for the Port of Churchill. Currently, the land at Churchill is rising at a rate of 9.3 mm/year, a product of glacial isostatic adjustment as the earth's crust responds to the melting of the ice sheets more than 10,000 years ago (Atkinson et al., 2016). This strong vertical uplift means that sea level at Churchill will continue to fall through the current century, despite rising global sea level. The projected range of sea-level decline at Churchill is about 35 to 40 cm by 2050, and 60 to 80 cm by 2100, although a decrease of more than 1 m is possible by 2100 (James et al., 2014) (Figure 6). Even under a very high global sea-level rise scenario, sea level at Churchill would not likely rise by more than a few centimeters.

Figure 6: Projected changes in sea level for Churchill, Manitoba. Under almost all scenarios, sea level will fall as a result of glacial isostatic adjustments, despite the fact that global sea level will continue to rise. See Atkinson et al. (2016) for scenario descriptions and James et al. (2014) for projected sea-level changes by decade. (Source: Natural Resources Canada)



3.3 CLIMATE, WEATHER AND TRANSPORTATION IN THE PRAIRIES

Shifting climate and weather conditions will affect all modes of transportation in the Prairies. Examples of these impacts include:

- Damage to roads, railways, and other structures as a result of flooding, erosion, and landslides;
- Increased frequencies of freeze-thaw cycles over the short term, damaging roads, rails, and runways;
- Compromised frozen substrates of winter roads; and
- Increased rutting of heated pavement (Sauchyn and Kulshreshta, 2008).

The Prairies may also experience benefits associated with warmer winters, including:

- Cost reductions associated with non-ice road infrastructure;
- Reductions in the length and severity of the frost-affected season, potentially resulting in long-term repair and maintenance cost savings; and
- Reduced cold-weather damage to rails (Sauchyn and Kulshreshtha, 2008).

Each mode can be expected to respond differently to climate-related risks. Sections 4, 5, 6, and 7 discuss past climate impacts, future risks, and adaptation practices separately for road, rail, air, and marine.

4.0 ROAD TRANSPORTATION

4.1 IMPACTS ON ROAD INFRASTRUCTURE

Extreme precipitation events create problems for roadway drainage. Truckers in the Prairies report an increased frequency of roadway flooding during extreme precipitation events, which may be partly attributed to inadequate culvert capacity (Kim Graybiel, Saskatchewan Ministry of Environment, personal communication, 2015). Washout and bridge scour may also occur as a result of extreme precipitation (Transportation Research Board, 2008).

Greater variability in temperature contributes to more rapid deterioration of road infrastructure. It is expected that the Prairies will experience an increase in the frequency of freeze-thaw cycles by mid-century (Sauchyn and Kulshreshtha, 2008), stressing road surfaces and bridges and increasing renewal and replacement costs (Amiro et al., 2014). Extreme heat causes asphalt pavements to rut and bleed (Transportation Research Board, 2008).

Drought has also had negative impacts on road infrastructure in the Prairies. Greater Edmonton experienced drought conditions from 2014-2015, leading to severe cracking of roadways as a result of desiccation of clay sub-soils; this can be explained in part due to the removal of water by vegetation (Kelm and Wylie, 2008) – damage was particularly severe in neighbourhoods with mature tree stands. Wildfires occurring during droughts typically do not seriously damage road infrastructure, given the inflammability of pavements and the relatively brief duration of these events.

4.2 IMPACTS TO TRUCKING OPERATIONS

Precipitation poses issues year-round to truck operators, and standing water on roadways is a particular concern in spring (Alberta- and Manitoba-based trucking practitioners; Alberta Motor Transport Association Representatives, personal communication, 2015). Increasing instances of freezing rain and extreme precipitation over the long term increase the likelihood of accidents and reduced travelling speeds (Transportation Research Board, 2008; Andrey and Mills, 2003).

Wind is also a concern. More frequent high-intensity wind events in recent years have generated scheduling challenges and have increased safety concerns for trucking operators, particularly for long combination vehicles (LCVs) on highways (Alberta- and Manitoba-based trucking practitioners, personal communication, 2015).

While changing temperatures themselves do not significantly affect trucking operations, increased temperatures in the long-term may positively affect road transportation efficiency in the Prairies. To a point, higher ambient temperatures improve diesel fuel efficiencies (Lohse-Busch et al., 2013; Natural Resources Canada, 2016).

Additionally, wildfires (resulting from persistent dry conditions) continue to cause disruptions to road transportation seasonally throughout the region – road and highway closures often occur in conjunction with fire and smoke (CBC News, 2015a).

4.3 ADAPTATIONS FOR ROAD INFRASTRUCTURE

Provincial governments have been active in implementing adaptive strategies. For instance, Manitoba has initiated a program to flood-proof roads, focusing on key trade routes such as the Provincial Trunk Highway (PTH) 75 to the U.S. and routes to the west. This adaptive strategy includes elevating roads, increasing culvert capacities, redirecting water flows, and paving gravel roads to reduce washout risks (Transportation and the Environment Task Force, 2014).

Other infrastructure adaptations involve the use of flexible regulations. For example, Manitoba's Spring Road Restrictions program previously enforced fixed start- and end-dates for its axle-weight restriction season (Manitoba Infrastructure and Transportation Staff, personal communication, 2015). These restrictions minimize road damage from heavy trucks during the spring thaw when roadbeds are relatively soft. In response to more variable temperature and weather conditions, the program has been adjusted to allow variable start and end dates (Government of Manitoba, 2015b). The complementary Winter Weight Premium Policy has been similarly modified (Manitoba Infrastructure and Transportation Staff, personal communication, 2015). Adjusting these programs cost very little relative to their benefits.

The Government of Manitoba is also reviewing its approach to water control on roadways to maintain traffic flow during extreme rainfall. Adaptation strategies under consideration include:

- the use of larger drains and culverts to increase water-flow capacity;
- larger bridges capable of withstanding intense precipitation;
- the use of more appropriate erosion-control mechanisms such as riprap and dikes; and,
- installing devices capable of monitoring bridge scour in real time during significant flood events.

The province is also assessing design standards for provincial bridges and culverts to determine if updates are required to accommodate changes in climate, land use, surface water drainage, and flood vulnerability (Government of Manitoba, 2015c). Major floods in 2011 and 2014 catalyzed many of these efforts.

With respect to possible temperature extremes, Manitoba Infrastructure and Transportation currently requires that bridge and large-culvert construction materials be designed to withstand a temperature range of 80°C (-40°C to +40°C). To mitigate impacts of freeze-thaw cycles, highly durable and impermeable concrete mixes are required for bridge decks and curbs/barriers, reducing moisture infiltration and expansion (Government of Manitoba, 2015c).

Alberta's provincial government has undertaken climate risk assessments for road infrastructure. In June 2012, Alberta's Ministry of Transportation released its "Climate Change Risk Assessment and Adaptation Report for the Ministry of Transportation," a high-level assessment of risks posed by a changing climate to the province's transportation sector. It also identifies potential adaptation measures, developed in accordance with ISO 31000 Risk Management Principles and Guidelines. During the department's enterprise risk-management and business-planning processes, long-term risks (based on climate scenarios for the next 50 years) were considered along with risks in the near (2 -to 10-year) term. Plans also exist to review climate risks as new and updated climate change scenarios become available, and identify potential options to reduce the severity of impacts (ICF Marbek, 2012).

In June 2013, Southern Alberta experienced heavy rainfall followed by catastrophic flooding. Five people were killed, more than 100,000 were displaced, and damage exceeded $5 billion (see Chapter 9). In terms of insurable damages, it is the costliest disaster in Canadian history (Environment Canada, 2014). In response, Alberta announced several risk-mitigation actions. In November 2013, the provincial government announced $110 million (2014-2016) for a Flood Mitigation Program, providing funds to upgrade, retrofit, or replace road and bridge infrastructure at high-risk sites in advance of scheduled end-of-life replacement. Specific repairs and upgrades to damaged sites were expected to account for $40 million, with the remaining $70 million dedicated to high priority sites susceptible to flood damage (Government of Alberta, 2013). Additional adaptive measures undertaken are discussed in Case Studies 1 and 2.

In addition to these long-term planning initiatives, Alberta government representatives indicate that a case-by-case approach to infrastructure adaptation is being taken in the province. Calgary's 2013 flood is often cited as motivation for efforts to reduce extreme-weather risks; however, most damage occurred in known floodplains. While changing climate factors may have contributed to high water levels, development in vulnerable areas was a factor contributing to the magnitude and costs of the damage (Alberta Government Staff, personal communication, 2015).

Saskatchewan's provincial government is attempting to build climate risks into asset-management processes, although budget realities often make the final determination (Kim Graybiel, Saskatchewan Ministry of Environment, personal communication, 2015). In response to extreme weather events, Saskatchewan's culvert program alters design requirements for National Highway System infrastructure from 1-in-25 year flood-event thresholds to 1-in-50 year events. For vulnerable communities, standards are being changed from a 1-in-50 year event to a 1-in-100 year event (Transportation and the Environment Task Force, 2014). The objective of this strategy is to facilitate more efficient overland movement of water, to reduce incidences of water being held back by road or rail beds to the point where washouts occur.

CASE STUDY 1

CASE STUDY 1: ALBERTA TRANSPORTATION'S ADAPTATION EFFORTS IN THE ROAD SECTOR

Alberta Transportation has developed a number of initiatives that consider climate and extreme weather in highway and bridge design processes. Highlights include:

Bridges: Following the June 2013 flood, Alberta Transportation reviewed its standards for sizing, configuring, and protecting bridge openings. The Department concluded that existing standards were appropriate, and no changes were proposed – most damage occurred at older crossings not designed to current standards. Risks to stream crossings associated with increasing frequency and magnitude of storm events were also assessed, and were considered low for the following reasons:

- Stream crossings are sized to match the capacity of the stream channel. It takes decades (or longer) for natural channels to change permanently in response to climate changes. Therefore, there is a low risk of sudden change in bridge-opening capacity requirements.
- Sizing of bridge openings is not overly sensitive to small changes in design flow (e.g. <20 percent).
- The frequency of longer-duration storms that cause flooding in large natural basins is not considered likely to change in comparison to the frequency of high-intensity, short-duration, limited-area storms. This concurs with the absence of observed significant trends in frequency or magnitude of storms in the province's 150-year historical record.

Bridge-deck drainage design requirements were also evaluated, focusing on sites where drainage blockages have occurred and maintenance is commonly required. Localized, high-intensity weather events are difficult to predict in timing or magnitude, and are more common than large regional floods. As a result, the most cost-effective method to address culvert blockages is to design infrastructure in ways that facilitate proper maintenance, a policy reflected in conceptual design guidelines for bridges in the province. For instance, a culvert structure at Malcolm Creek (built in the late 1990s) was filling with debris almost annually (not due to storms) and costs to clear the opening were significant. The culvert was recently replaced by a bridge configured to be more easily maintained (relocation was not feasible). Similarly, concrete box culverts at Cougar Creek were prone to blockage, and are now designed to be cleared by machinery. Finally, the Drystone Creek Bridge was designed with the knowledge that a significant portion of the opening would be filled in periodically.

Surface engineering: Observed temperatures are considered in two design procedures related to roadway-surface engineering. The first is pavement-thickness design – daily ambient temperatures provide an input to pavement-response modeling under various traffic loads. The second is the selection of asphalt mixes: traffic loadings and summer temperatures are the main inputs in selecting asphalt binders and mix types (rutting is a primary concern). In each case, Alberta Transportation considers changes in climate factors minor compared to changes in other factors such as traffic loads and changes to allowable axle combinations or tire sizes; however, both procedures can be adjusted to reflect future temperature and precipitation projections. Note that increasing storm frequency and intensity is not currently considered in these procedures.

Geotechnical engineering: On average, Alberta experiences one "debris flood" (differing from hydraulic floods by the amount and type of sediment carried) per year. These events are common in mountainous terrain when three-day rainfall exceeds 300 mm. During the extreme rainfall in summer 2013, more than 70 were recorded in a two-day span, blocking roadways and culverts. Alberta Transportation designs mountain creek bridges and culverts for hydraulic floods; however, 2013's events provided an opportunity to re-evaluate conventional hydraulic sizing criteria to consider debris flooding, which were not previously considered in the risk-management framework. Mountain creeks behave less predictably than rivers in the Prairies, and require different design criteria. Alberta Transportation is in the process of determining if risk-mitigation options are required, feasible, and economically-viable to deal with future debris flow events. A less-understood impact is the significant increase in tractive and erosive forces within debris floods and the action of these forces on mountain creek beds/banks. Predicting how streams will change course is difficult, as is determining the resilience of Alberta's highways to future debris floods.

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More frequent intense rainfall events also increase the risk of slope failures. Small failures may have no immediate impact on the driving surface, but over time may block ditch drainage (if located on the backslope), or eventually reach the pavement (if located on the foreslope). Alberta Transportation has not changed slope design criteria to meet these design conditions, as the cost to make all slopes more rain-resistant would be prohibitive. Standard designs are in development to allow staff to repair shallow slope failures at minimal cost.

Written with input from Peter Dzikowski and staff at Alberta Transportation.

CASE STUDY 2

CASE STUDY 2: CLIMATE VULNERABILITY ASSESSMENT FOR QUESNELL BRIDGE, CITY OF EDMONTON

The Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol, led by Engineers Canada, was developed as a 5-step process to analyze the engineering vulnerability of individual infrastructure systems based on current climate and future climate projections. One of the first PIEVC assessment projects in Canada was undertaken at Quesnell Bridge in Edmonton, Alberta. This assessment was unique in that the bridge had reached the end of its lifecycle and was scheduled for refurbishment; therefore, many components were reconsidered in light of the protocol's recommendations. The study concluded that while "generally robust", the bridge faces a number of future vulnerabilities to likely increases in the frequency and intensity of extreme weather events, such as:

- wearing of the bridge's exposed deck surface and water-proofing membranes, and
- overloading of the deck drainage systems and retention pond.

The PIEVC assessment identified risks to operations/maintenance (e.g. snow clearing) and serviceability/safety from future combinations and sequences of extreme events (e.g. road flooding, icing). As a result, the study recommended that the bridge's design criteria be updated to include changing annual climate loadings and extreme weather events under climate change scenarios; in some cases, climate data contributing to the development of rehabilitated infrastructure components (surface and drainage) dated from the 1960s (City of Edmonton, 2008).

Reconstruction of the bridge was completed in 2011. The PIEVC assessment informed waterproofing and paving of the bridge's west side, the creation of new stormwater-management facilities, and the addition of two general-traffic lanes and one transit-priority lane (City of Edmonton, 2011).

Written with input from Hugh Donovan (City of Edmonton)

4.4 ADAPTATIONS FOR TRUCKING OPERATORS

Trucking firms in the Prairies are adapting operations in a number of ways. For instance, truckers are adapting to more frequent high winds by choosing single trailer loads rather than doubles more often to reduce the potential for blow-over (Bison Transport Staff, personal communication, 2015). Due to high winds and bad weather, road tractors pulling double loads are sometimes required to drop off the rear trailer at a waypoint along their route, particularly if the second trailer is particularly light or empty (Bison Transport Staff, personal communication, 2015).

Truckers are also adopting technologies that enhance operational resilience to changing climate variables, although this tends to be a secondary benefit. For example, aerodynamic adaptations such as fairings and trailer skirts tend to be used to save fuel, but also enhance stability during wind events. Auxiliary power units (APUs) used by trucking firms are being refined and improved to respond to increased frequency of cold snaps or heat waves and reduce fuel consumption while idling. APUs provide non-idling power for on-board systems during the truck's "down time" at the side of the road or in rest stops. New APU designs are more appropriate for a wider range of environmental conditions, although this adaptation represents a major expense for trucking firms. Commercial trucking dispatch networks and other third-party "dashboard" providers have also been proactive in forwarding road condition information to road-tractor fleets.

Trucking firms have also devoted greater resources to weather monitoring, in some cases creating full-time positions for real-time monitoring of weather events throughout a firm's network. Some estimates suggest that there has been a five-fold increase in staff time spent on weather monitoring, with real-time linkages to dispatch offices. This enhances trucking firms' ability to quickly redirect traffic in response to traffic disruptions (Bison Transport Staff, personal communication, 2015).

Provincial governments also provide monitoring services to aid traffic flow. In Saskatchewan, the Road Conditions Highway Hotline is regularly updated with current information provided by road users and Government staff, available through multiple delivery systems (high-speed and low- bandwidth internet, RSS feed, and plain text) (Government of Saskatchewan, n.d.). Similarly, the Government of Manitoba operates a Road Weather Information System (RWIS), which uses road sensors and cameras to supplement staff inspections. This technology primarily focuses on extreme events such as snow storms, flooding, and construction delays on high-traffic routes, although some lower-traffic routes and winter roads are within its reporting range. Travelers can monitor road conditions via websites, email updates, and social media (Government of Manitoba, 2015d). In Alberta, road information (including weather and traffic delays) is also available online.

4.5 WINTER ROADS

Winter roads face a number of unique challenges related to increasing temperatures. While season lengths vary by road, most ice roads in the Prairies operate for approximately eight weeks from mid-January to mid-March. Research suggests that warmer winters are having a negative impact on winter-road construction and maintenance costs, as well as reducing the reliability and operating-season length (Federal/Provincial/Territorial Sub-working Group on Northern Transportation, 2015). However, recent data suggest these findings are not consistent throughout the Prairies. In Alberta, the Fort Chipewyan road has experienced a slightly longer season in recent years (Federal/Provincial/Territorial Sub-working Group on Northern Transportation, 2015). In Saskatchewan, the Cumberland House road may have experienced slightly delayed opening dates in recent years, but closing dates have also been delayed (Federal/Provincial/Territorial Sub-working Group on Northern Transportation, 2015). Manitoba is also experiencing irregularities in the winter road season (Case Study 3).

Shorter winter road seasons can result in significant social and economic impacts. Governments and businesses use these roads to transport important supplies such as chemicals, fuel, and other daily essentials for residents, businesses, and public utilities (CBC News, 2012a). Residents use ice roads to access urban areas and purchase supplies in bulk, reducing the household impact of high living-costs in remote northern communities. If ice is not thick enough for transit by mid-January, a modal shift from trucks to aviation for essential goods is required, at great expense to all users (Taylor and Parry, 2014). When ice roads eventually open in mild winters, load restrictions can be applied (CBC News, 2012b). Recent winter-road experiences in Manitoba are discussed in Case Study 3.

CASE STUDY 3

CASE STUDY 3: WINTER ROADS IN MANITOBA

Manitoba has the majority of the Prairies' winter roads (78 percent of winter road km), serving 30,000 people in 28 remote communities (Taylor and Parry, 2014). In Northern Manitoba, winters from 1998 to 2003 and 2009 to 2012 featured below-average operating seasons on most roads (Taylor and Parry, 2014; Table 1). Between 2007 and 2011, the average cost of the winter-road network rose to $13 million annually, and funding for winter roads has tripled since 1998 (Rabson, 2012; Manitoba Infrastructure and Transportation, 2011). In 2012, the province's 2500 km network opened several weeks later than normal, prompting Northern Chiefs to declare a state of emergency (CBC News, 2012b).

Despite a decline in season length from 2009 to 2012, data for routes in Manitoba (Table 1) suggest operating windows have recovered in recent years. Seasons from 2013 to 2015 slightly exceeded the 12-season average from 2003 to 2015 (48 operational days). Over this period, MIT recorded opening and closing dates for up to 50 distinct road segments operated in the major East Side Lake Winnipeg (ESLW) area. Routings were frequently changed, often to move the roads off ice-covered waterways and onto land routes (Taylor and Parry, 2014). Routing changes presented some challenges in efforts to quantify winter-road operating days, but these changes likely extended operational seasons for many routes. A shift towards more land-based roads has also offered greater safety during construction, maintenance, and use (Taylor and Parry, 2014). However, operating days are not the only relevant variable – many factors are involved in determining the relative success of different winter road seasons in moving goods to remote areas in recent years. These include routing changes, the polar vortex breakup of 2013-2014, varying weight restrictions, frost depth, snow cover, etc.

Future projections estimate average loss to the province's future ice-road season at eight days by the 2020s, 15 days by mid-century, and 21 days by the 2080s (Sauchyn and Kulshreshtha, 2008). In light of these expected impacts, more drastic adaptation efforts – beyond shifting routes from waterways to land – are being made to improve reliability, particularly for remote communities. For example, Manitoba is undertaking a large-scale infrastructure program ($3 billion over 30 years) to build permanent, all-weather roads in the ESLW area to serve remote communities with a collective population of approximately 36,000 individuals (Manitoba East Side Road Authority, n.d.). The proposed routing of this network closely approximates the current winter-road network. While the rationale for this undertaking is multi-faceted, the following supportive statement was made by the Eastside Road Authority " … over the years, the reliability and length of time that the winter roads are open has been lessening, resulting in hardships for local residents" (Manitoba East Side Road Authority, n.d.).

Other potential adaptations being considered include shifts to modes less costly than conventional aviation such as, enhanced rail and ferry services (Manitoba Infrastructure and Transportation Staff, Government of Manitoba, personal communication, 2015). Manitoba Infrastructure and Transportation currently operates four ferries during open-water season. These ferries serve remote communities reliant on winter roads, in the areas of South Indian Lake, Split Lake, York Landing, Bloodvein, and Norway House (Taylor and Parry, 2014). Others have proposed airships as a potential substitute for ice roads and conventional aviation (CBC News, 2015b).

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Table 1: Seasonal operating days for winter roads in Manitoba's ELSW region, constructed by combining Manitoba Infrastructure and Transportation data from winter-road segments from 2003 to 2015. The average number of operating days over this period of analysis for all recorded routes is 48. Cells marked N/A refer to unavailable data.

Manitoba East Side Winter Roads, days open seasonally, 2003-2015													
Road Location/ Communities Served	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	Route average
Bloodvein/ Berens River/ Poplar River	59	64	46	56	69	66	50	59	50	74	76	66	61.25
Pauingassi/ Little Grand Rapids	50	30	16	40	49	61	30	41	37	53	57	32	41.33
Bloodvein or Little Grand Rapids to Island Lake Area	53	38	26	N/A	42	48	35	36	29	25	N/A	N/A	36.88
Western Access to Island/ Oxford/ God's Lake Area	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	34	59	71	71	58.75
St. Theresa Point/ Wasagamack/ Garden Hill (internal)	47	34	33	N/A	46	57	27	40	31	42	55	56	42.55
Seasonal average (all routes)	52.25	41.5	30.25	48	51.5	58	35.5	44	36.2	50.6	64.75	56.25	48.15

12-year average, all routes

Written by Will Towns and Al Phillips

5.0 RAIL TRANSPORTATION

5.1 PAST IMPACTS AND FUTURE RISKS

EXTREME PRECIPITATION

Rail company geotechnical engineers cite challenges with surface water and drainage related to extreme precipitation, including the fouling of track ballast and increasing risks of washouts. Fouling limits the ballast's ability to shed water away from the track area (Michael Hendry, Canadian Rail Research Laboratory, University of Alberta, personal communication, 2015) and reduces the resistance of rail infrastructure to frost heaves (shifting soil or rock during freezing conditions) (Nurmikolu and Silvast, 2013).

Anecdotally, standing water is an increasing problem. One long-time regional geotechnical expert indicated seeing water against-grade in Saskatchewan in places not seen in 30 years in the business (Tom Edwards, Canadian National Railway, personal communication, 2015). The situation is particularly problematic if culverts freeze in spring. Frozen culverts restrict water flow, increasing the risk of washout and the likelihood and severity of track damage (Figure 7) (Michael Hendry, Canadian Rail Research Laboratory, University of Alberta, personal communication, 2015).

These consequences affect reliability and efficiency of rail movement, as well as profitability, as rail companies typically own infrastructure and incur any necessary costs to maintain tracks to federal standards.

Figure 7: Sub-grade collapse and train derailment due to a frozen culvert in Togo, Saskatchewan, 2013. (Source: Transportation Safety Board of Canada)

EXTREME TEMPERATURES

The ideal temperature range for freight-rail operations is -25°C to +25°C (Miller, 2014). While thermal rail expansion (buckling due to heat) has rarely been cited as an issue in the Prairies, extreme cold is a major concern for winter rail operations (Boyle et al., 2013). In cold temperatures, steel tracks (continuously welded rail) and wheels become more brittle and susceptible to breakage, and air-braking systems become more prone to leaks and freezing. A review of Transportation Safety Board of Canada rail incident reports suggests that cold weather-related rail fractures have contributed to some derailments in the Prairies (Transportation Safety Board of Canada, 2013). Cold temperatures also create operational issues by limiting the safe length of trains. According to the Rail Association of Canada, the maximum safe length of an intermodal train with distributed power decreases by 15 percent below 25°C and 39 percent below -35°C. Shorter trains operating in a network near capacity with relatively long cycle times results in cascading effects throughout the rail system. Increased congestion in terminals limits efficiency, while greater train density in a given area results in more trains encountering one another, increasing use of sidings and further reducing average speeds (Miller, 2014). Extreme cold temperatures were an important contributing factor to delays in grain handling in the winter of 2013-2014 (Case Study 4).

While instances of extreme cold are projected to decrease in the Prairies, these periods will still occur at unpredictable intervals (Bush et al., 2014). During periods of extreme heat in the 21st century, rail buckling risks will also increase (Transportation Research Board, 2008). These impacts illustrate both current and future risks posed by temperature extremes to rail-freight transportation.

CASE STUDY 4

CASE STUDY 4: RAIL-FREIGHT MOVEMENT IN WINTER 2013-2014

Moving grain to port via rail in the Prairies in the winter of 2013-2014 has been described as a "perfect storm" of issues (Cash, 2014). Grain handling in the region is a complex process involving many actors. In this particular year, a series of events and conditions complicated the process further, including:

- an above-average Prairie crop yield;
- the removal of the Canadian Wheat Board single-desk marketing mechanism;
- increased orders for car placement by grain companies wishing to move product;
- delayed initial orders for car placement; and
- an extremely cold winter in the Prairies (Miller, 2014; Atkins, 2014).

As illustrated in Figure 8, most of the Prairies experienced lower-than-average temperatures in winter 2013-2014 – up to 4.5°C lower in some areas. The following discussion is based primarily upon information regarding CN operations during this period.

In the 2013-2014 winter season, trains operated below the -25°C threshold more frequently than normal (Miller, 2014). Rail companies experienced several difficulties, including air brake hose leaks (compromising braking capacity), more frequent rail breaks (200 percent higher than non-winter norms), and more frequent steel wheel breaks.

In response, rail companies reduced train lengths and speeds. Average grain-train length was reportedly 70 percent as long as it could have been under ideal temperature conditions. This caused a cascading effect, primarily driven by increased network congestion.

Average train speed was also reduced over this period. In winter, trains normally operate at speeds approximately 8 percent lower than in other seasons. In 2013-2014, this reduction was approximately 13 percent. As a result of shorter and slower trains, the car-order fulfillment rate (the ratio of orders filled on schedule to orders placed) decreased by over 30 percent compared to non-winter seasons, compared to the winter norm of 15 percent.

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Figure 8: Temperature departures from the 1961-1990 average experienced in Canada during winter 2013-2014. (Source: Environment and Climate Change Canada)

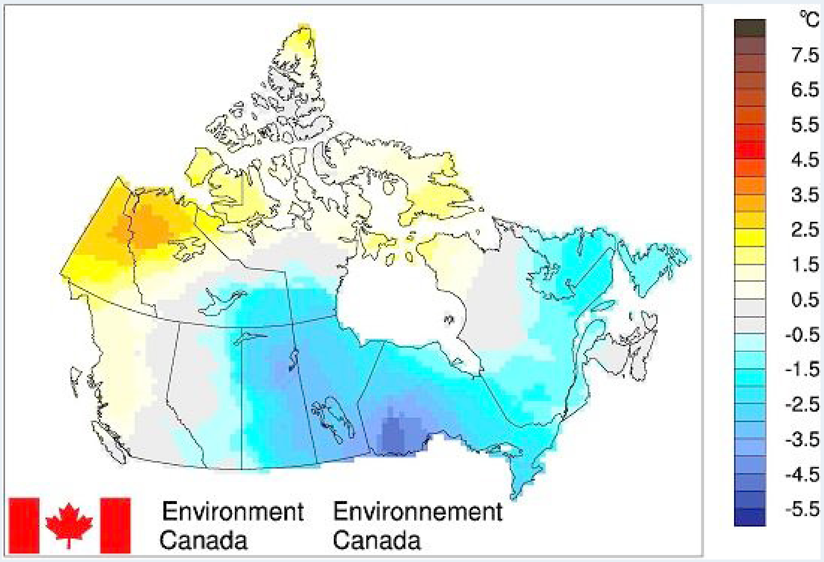

Figure 9a shows weekly rail transit times for trains going from British Columbia ports to Toronto. Two pronounced spikes in transit time are apparent. The first corresponds to a rail labour strike in 2012, while the second corresponds to the extreme cold winter of 2013-14.

Figure 9a: Weekly rail transit times from British Columbia ports to Toronto.

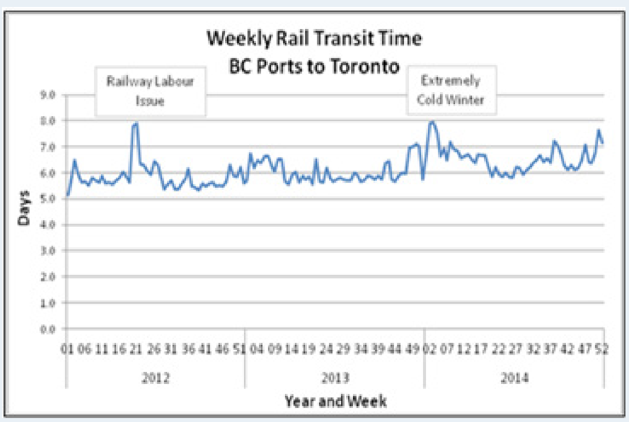

Figure 9b: Centralized traffic control outages - % increase in winter vs. non-winter. (Source: Railway Association of Canada)

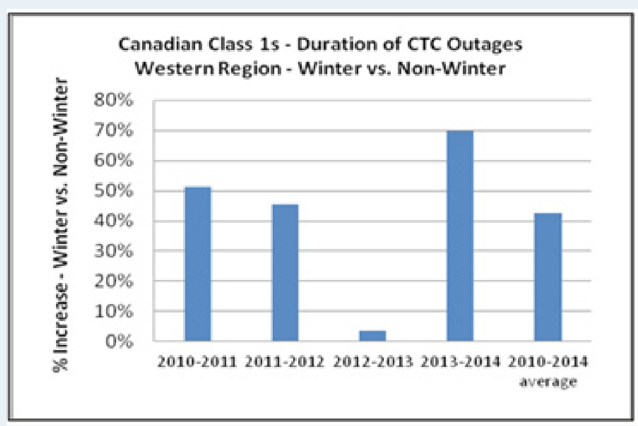

Figure 9b illustrates a critical measure related to lower train speeds, higher dwell times and more re-crews - the number of "centralized traffic control" (CTC) outages. These outages mean that normal centralized dispatch systems are down, requiring slower train movements and positioning until the system is normalized. The bar graph shows the significant increase in CTC outages in 2013-2014, creating systemic vulnerability.

Written by Al Phillips

OTHER CLIMATE RISKS

Increasing freeze-thaw cycles (a trend expected to continue) are generating more frequent rockslides, affecting rail operations in mountainous areas (Middleton, 2000). Freeze-thaw cycling also creates problems for track stability, particularly in the region's northern reaches (Middleton, 2000).

Extreme snow and wind events can delay rail services, particularly in combination. Strong winds are expected to present scheduling challenges in future, requiring trains to reduce speeds or move to sidings (Miller, 2014).

Hudson Bay Railway is uniquely affected by permafrost thaw. This line is critical to operations at the Port of Churchill, and also for local residents – grain-car derailments have resulted in passenger service cancellations due to the absence of alternate routes (Wang et al., 2016). Reliability may become increasingly difficult to maintain if adaptations are not made (Case Study 5).

CASE STUDY 5

CASE STUDY 5: RAIL IN THE HUDSON BAY LOWLANDS: A SPECIAL CIRCUMSTANCE

Manitoba's most northerly rail line (terminating in Churchill) faces challenges associated with thawing permafrost and muskeg (Tweed, 2015). Muskeg provides a poor base for rail, primarily due to its low compressibility (Lautala et al., 2008). Rail shifts, sinks, or even rises as a result of frost heaves in these areas. The Hudson Bay Railway Rehabilitation program, an initiative jointly funded by the governments of Manitoba and Canada in partnership with the line's operator, OmniTRAX, is a 10-year undertaking specifically designed to reduce the impacts of permafrost degradation and warmer temperatures on rail service, particularly from The Pas to Churchill. This initiative involves stabilization of the rail bed – to date, about $50 million has been spent on rehabilitation of the Bay Line since the program began in 2008 (Wang et al., 2016).

However, rail-line rehabilitation has not been as successful as initially hoped, due to challenges associated with the discontinuous permafrost and muskeg terrain. The rail line (and its original ballast) was laid over the winter of 1928-1929 atop frozen muskeg, the season when track stability is greatest. As temperatures warm, the ballast has been dissipating into the muskeg, resulting in more frequent remediation. For example, in June-July 2014, OmniTRAX added 40,000 tonnes of ballast under the Gillam-to-Churchill section of the rail line (Tweed, 2015), following the previous year's remediation effort, which added 15,000 tonnes of ballast. The company now considers backfilling an operational rather than a capital cost. Recent research (Addison et al., 2015) confirms that stabilization measures have not been effective, and that deterioration is accelerating.

Given projections for long-term warming in the Hudson Bay Lowlands, supporting the rail bed will become increasingly difficult. In response, geotechnical engineers are developing adaptation strategies.

As permafrost thaws, some technical efforts to stabilize the railway will increase in costs and difficulty (Wang et al., 2016), although others may become more feasible. One proposed measure involves lifting the track and adding a layer of gravel to insulate permafrost (enhancing stability), although the continued maintenance required makes this option challenging (Wang et al., 2016). Another approach to stabilizing muskeg in the rail bed involves mixing cement with the vegetative mat (provided shifting muskeg can be controlled); however, this option requires further testing and evaluation given that frozen substrate makes it difficult to mix cement into the muskeg (Eddie Choi, Canadian Pacific Railway, personal communication, 2015). Permafrost thaw may enhance the viability of this stabilization technique, although the long-term effectiveness remains uncertain.

Written by Al Phillips and Will Towns

5.2 RAIL ADAPTATIONS

A common adaptation to extreme rain events in the Prairies is to enhance culvert capacities. For example, the Canadian National Railway (CN) is planning to install main-line culverts with a capacity for 1-in-100 year rain events and enhance the capacity for branch lines culverts to a 1-in-50 year threshold. Some municipalities promote a 1-in-500 year threshold when negotiating culvert upgrades with railways (Mario Ruel, Canadian National Railway, personal communication, 2015). Geotechnical engineers indicate that while decisions are made on a case-by-case basis using the project engineer's best professional judgment, a shift in perspectives is underway. While 1-in-100 year events have been the standard in the past, 1-in-200 year criteria are becoming a more common benchmark (Tom Edwards, Canadian National Railway, personal communication, 2015).

In some parts of the Prairies, rail and rail bridges are also being raised to higher grades in response to seasonal flood risks (Manitoba East Side Road Authority Representatives and Manitoba Floodway Representatives, personal communication, 2015). For example, along Winnipeg's Red River Floodway, rail (and road) bridges have been raised to a 1-in-700 year event threshold (see Case Study 6).

In response to the increasing frequency of high-intensity wind events (both experienced and projected), wind sensors are being affixed to some rail bridges in the Prairies, particularly on the highest structures (Mario Ruel, Canadian National Railway, personal communication, 2015). With advance warning of high-intensity wind, train operators can delay passage over rail bridges, or adjust speeds accordingly.

BNSF reports a greater use of snow fences on its network (Amiro et al., 2014). These assist in keeping tracks clear of snow drifts in the winter.

CASE STUDY 6

CASE STUDY 6: ROAD AND RAIL CONSIDERATIONS IN THE RED RIVER FLOODWAY EXPANSION PROJECT

The Red River Floodway is designed to protect the City of Winnipeg, including its transportation infrastructure, from spring runoff flooding along the Red River, although it can be utilized during other times in response to extreme precipitation events in the watershed. Since 1968, it is estimated that the artificial floodway has prevented more than $40 billion (in 2011 dollars) in flood damage to Winnipeg. The structures and systems associated with the Floodway are collectively recognized as a National Historic Civil Engineering Site and considered one of the world's 16 engineering marvels (Government of Manitoba, 2011).

While the Floodway has operated well since its completion in 1968, recent severe flood events have caused planners to rethink the expected frequency of flood-disaster potential. The structure was designed to handle 60,000 cubic feet per second (cfs) of water, considered sufficient to protect Winnipeg from a 1-in-90 year event. Later upgrades brought the channel capacity to 90,000 cfs. A major flood in 1997 reinforced concerns about the future frequency of extreme flooding, and planners began to consider that events formerly referred to as 1-in-200 year events may become 1-in-20 year events. In response, floodway capacity was further increased to 140,000 cfs to provide protection for a 1-in-700 year event, a capacity beyond the river's largest flood on record (which occurred in 1826).

Expected shifts in climate and extreme weather were the main drivers behind the expansion of the Red River Floodway, but these changes were made for economic reasons as well. In the absence of road and rail bridge upgrades over the floodway channel, east-west road and rail movements and access to the Mid-Continent Corridor could be stopped or seriously curtailed during a flood event. This would have serious economic implications beyond Manitoba. A significant percentage of Alberta, Saskatchewan, and (to a lesser extent) Ontario trade destined for U.S. markets is routed through the I75/I29 portal.

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Adaptive road and rail measures formed a major part of this expansion. Bridges were raised and piers modified to ensure road and rail traffic could continue unimpeded on the road network traversing the now-expanded floodway channel. Examples include:

- **PTH 59 South Highway Bridge:** Two existing northbound and southbound road bridge structures were replaced. The new bridge structures are 4 m higher and 50 m longer than the previous structures.
- **Trans-Canada Highway Bridge:** The original bridge was replaced with two new bridge structures, 3.9 m higher and 98.6 m longer than the original bridge.
- **PTH 15 Highway Bridge:** The PTH15 Highway Bridge was replaced with a new structure approximately 1.9 m higher than the previous bridge, with additional modifications.
- **PTH 44 Highway Bridge:** The PTH 44 Highway Bridge was replaced with a new structure 0.9 m higher and 16 m longer than the previous structure, along with intersection improvements.
- **CN Sprague Railway Bridge:** The Sprague Railway Bridge, carrying the CN line, was replaced by a new bridge approximately 77 m longer and 2.7 m higher than the previous structure.
- **CN Redditt Railway Bridge:** The new CN Redditt Railway Bridge is approximately 34 m longer and 2.3 m higher than the previous structure.
- **CP Keewatin Railway Bridge:** The new CP Keewatin Railway Bridge is approximately 37 m longer and 1.3 m higher than the previous structure.

While not specifically part of the Red River Floodway expansion, plans are underway to raise the level of PTH 75 south to the U.S. border in line with the level of Interstate-29 south of the Canada-U.S. border. This, in conjunction with the expansion of the Red River Floodway, will enhance the reliability of trucking along the Mid-Continent Corridor and its east-west linkages that connect Alberta, Saskatchewan and Manitoba to central U.S. markets.

Written by Al Phillips

6.0 AVIATION

6.1 PAST IMPACTS AND FUTURE RISKS

Aircraft operators in the Prairies report several operational challenges associated with changing climate conditions and extreme weather, including:

- increased de-icing requirements,
- greater frequency of flight delays occurring because the destination airport is closed,
- wind events affecting approach-scheduling, and
- cargo weight restrictions due to soft runways.

Greater frequency and severity of extreme weather (particularly precipitation) events are a major concern for aviation in the Prairies. Some air carriers operating in the Prairie provinces have reported an increased frequency of flight delays or cancellations, mainly in response to precipitation and fog events. Airport representatives and provincial administrators of non-National Airport System airports and aerodromes have similarly cited concerns with a greater frequency of these events.

Air operators in the northern Prairies have observed more significant changes than have operators in the south, and practitioners suggest that the costs of weather variability have been particularly difficult for small operators to internalize. The resilience (or adaptive capacity) of southern airports is generally higher than their northern counterparts as a result of more readily-available ground equipment and system redundancies (Calm Air Representatives, personal communication, 2015).

Smaller airports in the northern Prairies have experienced specific challenges with standing water on runways. Particularly in springtime, precipitation percolates into the runway base, softening the surface area. When aircraft land on these softened runways, depressions are formed, allowing greater opportunity for the accumulation of standing water. In an effort to minimize the formation of depressions, carriers reduce their payloads (Calm Air Representatives, personal communication, 2015).

One carrier indicated that over the past few years, their operation had experienced a significant increase in delays due to weather variability, particularly in the northern Prairies. This has partly contributed to an increased need for aircraft de-icing. Increased variance in temperature has resulted in a greater frequency of ideal conditions for ice formation on the control surfaces of aircraft (Calm Air Representatives, personal communication, 2015). De-icing stations are rare in northern Prairie communities, often resulting in prolonged delays for aircraft departures.

Extreme cold also affects aviation operations. All aircraft have a range of temperature for which they are certified. This temperature range varies by aircraft, and by variant within an airframe type. An aircraft may be grounded, and prevented from making its return flight if temperatures drop quickly during its flight. In the Prairies, low temperatures currently pose a greater operational risk than high temperatures. For instance, in the cold winter of 2013-2014, some U.S. carriers’ scheduled flights to western Canada were cancelled because the aircraft were only certified to -30°C. Such scheduling disruptions have been reported to occur with greater frequency in response to more rapid temperature shifts, something to which the Prairies is prone.

6.2 ADAPTATION PRACTICES

INFRASTRUCTURE

Modifications have been made at airports in the Prairies to improve the ability of runways to shed precipitation (Perimeter Aviation Representatives, personal communication, 2015). For example, certain types of sealants are being used on gravel airstrips. These involve applying a ¾" to 1" thick layer of a water-shedding material, although the runway is still classified as a treated gravel airstrip. These sealants are used on some runways in Saskatchewan and Alberta, although are not yet reported on Manitoba gravel airstrips. The sealant assists in reducing the percolation of moisture into the runway base material, and instances of standing water, which helps to reduce traction issues for aircraft trying to land on shorter runways (International Civil Aviation Organization Secretariat, 2010).

OPERATIONS

Air carriers operating in the Prairies report some changes to operations and equipment to better manage the challenges posed by weather and changing climate conditions. As an adaptation to scheduling disruptions in remote northern communities, carriers have expanded ground facilities (warehousing) so freight aircraft that have been delayed can offload outside the community's normal business hours and continue on their route. Ground transportation services can then pick up and distribute freight during business hours. Carriers in northern communities that lack de-icing stations are also using portable de-icing mechanisms to deal with more frequent icing.

To adapt to more frequent fog events, one carrier in Saskatchewan has reported making scheduling changes to allow fog to dissipate, moving early morning departures to late morning for some communities (Lloyd Epp, West Wind Aviation, personal communication, 2015).

A potential adaptation to disruptions caused by temperature certification issues is to reduce the number of different aircraft types or configurations in a given fleet. While there are other operational reasons for minimizing the number of aircraft types in a fleet (i.e. simpler maintenance requirements), consistency in air temperature certification is a factor in the Prairies.

7.0 MARINE TRANSPORTATION

This section identifies risks faced by vessels and ports in the context of a changing climate and patterns of extreme weather, and describes adaptive efforts to cope with these impacts. As the Prairies' only access point to tidewater, the following discussion of issues focuses specifically on Churchill and its unique situation.

7.1 FUTURE CLIMATE IMPACTS AND OPPORTUNITIES

The effects of global sea-level rise will not be experienced consistently across the globe. Certain areas in the higher northern latitudes, including Hudson Bay (and Churchill, Manitoba), are likely to continue to experience sea-level decline throughout the 21st century as a result of isostatic adjustment (glacial uplift) (Bush et al., 2014). Therefore, Churchill is likely to be one of the few ports in Canada not adversely affected by sea-level rise and more severe storm surges. At present, Churchill experiences 3 m tides. Increased mean temperatures are likely to result in a shorter sea-ice season, extending Churchill's shipping season (currently about 14 weeks). However, sea-level decline along Hudson Bay's western coast could increase navigational challenges for large vessels attempting to take advantage of the extended season.

7.2 MARINE INFRASTRUCTURE AND OPERATIONAL ADAPTATIONS

Transition measures were put in place to help the port adjust to the end of the Canada Wheat Board in 2012. Capital improvements funds were designed to encourage some diversity in port operations, expanding port capacity beyond its traditional focus on outbound bulk-grain handling to include other movement systems, including intermodal operations (Transportation and the Environment Task Force, 2014). Although these improvements are unlikely to be explicitly linked to climate change adaptation, a shift in short-sea shipping capacity may have implications for an extended marine resupply season. The owner and operator of the Port of Churchill reports that water levels at the wharves have been trending downwards, suggesting the only adaptation that would be required is dredging of the harbour (Jeff McEachern, OmniTrax Canada, personal communication, 2015).

The Port of Churchill's capacity to load vessels has been idle for much of each year, as the shipping season normally covers about 14 weeks from mid-July to late October. If the ice-free season is extended, more activity could be supported without substantial infrastructure improvements. Challenges remain for the Port of Churchill, although these are primarily inland, and deal with surface access to the port from southern shipping distribution points (discussed in Case Study 5).

Case Study 7 describes the results and recommendations of a recent PIEVC assessment completed for transportation infrastructure connecting Manitoba and Nunavut, including Churchill's marine components.

CASE STUDY 7

CASE STUDY 7: CLIMATE CHANGE VULNERABILITY AND THE MANITOBA-NUNAVUT SUPPLY CHAIN

A recent study (Duguid et al., 2015) examined key infrastructure supporting the supply of goods and services between Northern Manitoba and Nunavut's Kivalliq region. The project aimed to identify potential vulnerabilities associated with a changing climate, northern economic development, and growing populations. Climate change is likely to put direct physical stress on this northern supply-chain infrastructure, while simultaneously increasing demand and performance expectations. The study's recommendations included:

1. Development and use of an **integrated supply chain model** that supports a **systematic understanding** of how decisions could affect the supply chain as a whole.

2. **Integrated governance** for transportation infrastructure supporting the North.

3. **Integrated planning and strategic investment strategy** for northern transportation infrastructure.

The study analyzed the engineering vulnerability of the Port of Churchill, the Thompson Freight Services Hub, and the Rankin Inlet Airport to current and future conditions via the Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol. The assessment determined that none of the assets are at high risk of impact, although all three had numerous medium risks. It was recommended that medium risks be closely monitored and that most of these risks would affect operations, while very few would affect infrastructure. While some risks may be managed by increasing materials, labour, and costs, others cannot be controlled and in these cases, preparedness for interruptions and delays and regular maintenance of infrastructure were recommended.

However, while individual transportation facilities themselves may be relatively robust, the overall system may be vulnerable. The infrastructure – built with reference to historic levels of demand and climate trends – has been expanded on an ad hoc basis and focused on local needs, often without consideration for the impacts on the broader system and the communities it supports.

...

...

Examples of infrastructure vulnerabilities ("medium risks") that could have significant implications for the supply chain include:

- the rail line between Thompson and Churchill, which has been heavily and repeatedly affected by permafrost degradation and is vulnerable to delays and disruptions; and
- Highway 6 into Thompson, which may be vulnerable to closures due to forest fires or flooding.

Written with input from Naomi Happychuk (Northern Sustainable Prosperity Initiative, University of Winnipeg)

8.0 INFORMATION GAPS AND CONCLUSIONS

This chapter summarizes the state of knowledge on climate impacts, risks, and adaptation practices for transportation systems in the Prairies, based on available literature and practitioner experiences. Several gaps were identified during the course of research.

There is a lack of documented information on specific climate impacts and adaptation practices for transportation in the Prairies, suggesting few researchers have focused on this topic in the region.

There are gaps in climate data important to transportation operators. While long-term climate projections (temperature and precipitation) may be useful for long-term infrastructure planning, additional information would be useful on projected changes in the expected frequency and severity of extreme weather events. Prairie governments and operators have been investing in weather monitoring and communications to reduce risks from extreme weather, but more accurate predictions of the locations and timing of these events would be useful for short- and medium-term operational planning.

There are gaps in transportation data that make it difficult to analyze trends, particularly for specific modes at the provincial and regional level. For example, data is not reported on the frequency of aircraft being redirected to alternate airports, or the frequency of aircraft "go-arounds" (i.e. aborted landings), so it is difficult to determine if there have been changes in the impacts of extreme weather events on operational indicators at airports.

Despite these information gaps, governments and operators in the Prairies have been making efforts to reduce future climate risks to infrastructure and operations, particularly those associated with precipitation. Flood-control strategies, intended to reduce future risks of washout, represent key adaptation strategies in all three Prairie provinces.

At the same time, transportation operators in the Prairies have tended to take a reactive, case-by-case approach to climate and weather adaptation. As information and knowledge improves on longer-term climate risks, transportation decision-makers in the Prairies will be able to be more proactive in their adaptation efforts.

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6 · Ontario

CHAPTER 6: ONTARIO

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TABLE OF CONTENTS

KEY FINDINGS

- **Recent extreme weather events (in both summer and winter) demonstrate the vulnerability of Ontario's transportation networks to climate-related impacts.** The flooding of roads and rail lines in July 2013 and the ice storm of December 2013 in Southern Ontario resulted in significant damage and travel disruption, but also spurred greater organisational awareness of the region's vulnerability to more frequent extreme weather. Multiple resilience-enhancing initiatives have been undertaken in the wake of these events by public agencies, particularly for roads and rail.
- **Warming temperatures and changing precipitation patterns are expected to contribute to altered (increased or decreased) water levels in the Great Lakes basin, with implications for shipping capacity in the Great Lakes-St. Lawrence Seaway.** Fluctuations over the past 20-30 years make it difficult to predict the direction of long-term change; however, freight transportation may shift to other modes should trends toward lower water levels throughout the Great Lakes occur again.
- **The access period for winter roads in Northern Ontario is likely to decrease as a result of warming temperatures.** This carries economic impacts for remote northern communities; a modal shift from truck to air transportation is likely to be necessary if significant investments are not made in more resilient road infrastructure in Northern Ontario.
- **Practitioners in Ontario have begun to assess the vulnerability of their assets, and in some cases, adapt their infrastructure and operations in preparation for changing climate conditions.** Efforts made by the Ontario Ministry of Transportation (roads and bridges), Metrolinx (rail), the Greater Toronto Airport Authority (aviation), and the Great Lakes-St. Lawrence Seaway Management Corporation (marine shipping) reflect a diversity of adaptive practices employed in Ontario.

1.0 REGIONAL INTRODUCTION AND OVERVIEW

Ontario is Canada's second-largest province in terms of area, and largest in terms of population. While its population density (14.1 persons per km^2) is significantly higher than the national average (3.7 persons per km^2) (Statistics Canada, 2012), many areas of the province are remote, isolated from employment centres, urban markets, and international transportation hubs. Maintaining efficient and effective surface, marine, and air transportation systems for passengers and freight in this context is complex. A changing climate makes these challenges greater. Temperature and precipitation patterns are projected to shift considerably by mid-century, and projected increases in the frequency and intensity of severe weather events present serious risks for Ontario's transportation system (e.g. flooded roadways, lower water levels) and potential socioeconomic consequences (e.g., costs, disruptions), in the absence of effective adaptation action.

Not all effects of a changing climate will be negative. Most research has focused on the potential negative impacts of climate change, and positive impacts may not be well-understood (Chiotti and Lavender, 2008). While this chapter identifies potential opportunities and benefits as applicable, the primary focus is on transportation-related risks.

Ontario's transportation network will be discussed with reference to three distinct sub-regions (northern, central, and southern [see Figure 1]) in order to capture the province's geographic, social, and economic diversity; different capacities for climate change adaptation; and the unique adaptive measures required. While Ontario's adaptive capacity is relatively high due to its aggregate economic wealth, education levels, infrastructure, social capital, and institutions, this capacity is not evenly distributed throughout the province (Chiotti and Lavender, 2008). Each sub-region is described briefly in the following section in terms of environmental, social, and economic characteristics.
Note that while this chapter recognizes the importance of urban transportation networks in Ontario, municipal climate impacts and adaptation practices are discussed in Chapter 9.

This chapter involved an extensive review of both scholarly and grey (non-peer reviewed) literature, as well as interviews with transportation practitioners across the province. The findings and discussion reflect the current state of knowledge on climate adaptation in Ontario; however, they should not be considered an exhaustive inventory of experiences, impacts, and adaptations.

Figure 1: Boundaries of Ontario's three sub-regions. (Source: Natural Resources Canada)

1.1 GEOGRAPHY

SOUTHERN SUB-REGION

Ontario's southern sub-region extends from Canada's southernmost location (Point Pelee) east to the Quebec border. The topography ranges from flat in the southwest and southeast to rugged and hilly in the Niagara escarpment region (Chiotti and Lavender, 2008). It contains eight of Canada's 16 most densely-populated metropolitan centres, including the urban regions of the Greater Golden Horseshoe (centered around the Greater Toronto and Hamilton Area), and the City of Ottawa in the east. This sub-region features significant landscape modification for transportation networks, urban development, and agriculture. Southwestern Ontario has a temperate, humid climate, with warm summers and cold winters. For communities in this area, the Great Lakes have a moderating effect on temperature, influence patterns of atmospheric convection (and therefore precipitation distribution and intensity) during the summer, and produce a "snowbelt" effect in the winter (Baldwin et al, 2011; Gula and Peltier, 2012). Southeastern Ontario is characterized by relatively longer winters and shorter summers than in the southwest, although annual precipitation levels are comparable (Baldwin et al, 2011).

CENTRAL SUB-REGION

The central sub-region, which includes Sudbury, Thunder Bay, and Timmins, is composed almost entirely of the forested and rocky terrain of the Precambrian Shield. Its summers are humid and mild, and precipitation is distributed evenly throughout the seasons (Baldwin et al, 2011). There are many low-density, resource-dependent communities, notably in the forestry, pulp-and-paper, mining, and tourism sectors. It contains two-thirds of Ontario's highway system, which along with the rail network, is important in connecting the area's resource producers to markets in other areas of the province, country, and continent (Chiotti and Lavender, 2008). The sub-region's remote communities and extractive industries also depend greatly on more than 3,000 km of seasonal-access roads for economic well-being, social stability, and surface freight movement in winter (Ontario Ministry of Northern Development and Mines, 2013).

NORTHERN SUB-REGION

The northern sub-region extends from the upper boundary of Central Ontario to the coasts of Hudson and James Bay. The topography and landscape are largely low-lying and poorly-drained, containing the majority of the province's permafrost in the cryosolic (i.e. frozen) soils of the northwest (Baldwin et al, 2011). Northern Ontario has a subarctic climate, with long, severe winters and short, cool summers. Temperatures of -40˚C are common (although temperature is highly variable year-round), and annual precipitation is lower than in other sub-regions (Baldwin et al, 2011). Northern communities are also remote, and many rely solely upon aviation for connectivity.

1.2 SOCIAL AND DEMOGRAPHIC CHARACTERISTICS

Ontario is the fastest-growing province in Canada, with an estimated population of 13.8 million in 2015 (Statistics Canada, 2014, Table 1). Significant growth is expected to continue well into the 21st century, with implications for future demands on passenger and freight transportation systems throughout the province. Approximately 17.4 million people are projected by 2036 (Ontario Ministry of Finance, 2013).

Eighty-nine percent of the province's population lives within Census Metropolitan Areas (CMAs) or Census Agglomerations (CAs) (Statistics Canada, 2012). Most of the province's future growth will continue to be concentrated in urban areas; therefore, Ontarians will increasingly live and work in denser, more transit-accessible neighborhoods. The Greater Golden Horseshoe (GGH) in Southern Ontario will absorb most of this growth, primarily through immigration (Ontario Ministry of Finance, 2013).

Table 1: Population projections to 2036 for each sub-region, based on census data analysis by Statistics Canada and the Ontario Ministry of Finance. (Source: Ontario Ministry of Finance, 2013)[3]

Sub-region	2014 Population	2036 population	Rate of change, 2014-2036
Northern	35,435	46,203	+30.3%
Central	948,165	965,817	+1.8%
Southern	12,522,320	16,359,820	+30.6%
Ontario total	13,505,920	17,371,840	+28.6%

[3] Note that these regionally-specific population projections are approximate, given that the climate sub-regions fail to align perfectly with the jurisdictional boundaries used in the collection and analysis of census data.

Ontario is also home to the country's largest population of Indigenous people, approximately 242,495 of Canada's 1,172,785 First Nations, Inuit, and Métis (Aboriginal Affairs and Northern Development Canada, 2014). Indigenous populations in the central and northern sub-regions have unique vulnerabilities to climate-related impacts. For example, one in four First Nations communities in Ontario are accessible only by air year-round or ice- or winter-road seasonally.

1.3 ECONOMIC CHARACTERISTICS

The economies of Central and Northern Ontario are similar in many respects. While traditional economic activities, like mining, remain important in both sub-regions, diversification efforts are being made (Ontario Ministry of Infrastructure and Ministry of Northern Development, Mines and Forestry, 2011).

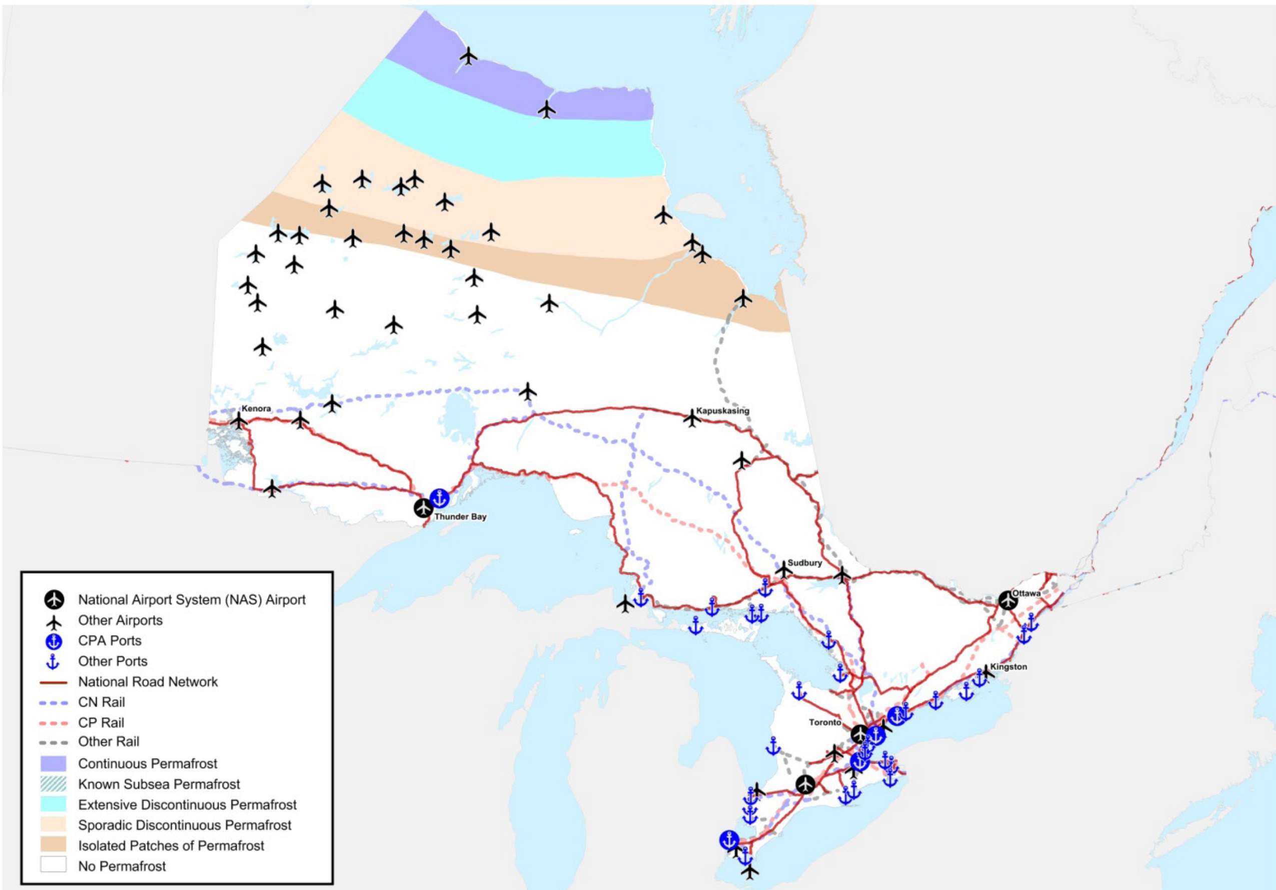
Central Ontario contains the majority of the province's 40 operational mines, representing significant economic opportunity (Ontario Ministry of Northern Development and Mines, 2013). Thunder Bay is a key transportation hub for air, rail, and marine-shipping traffic, while Sudbury's economic base includes mining, resource-processing, tourism, and education. Northern Ontario's main industries include mining and tourism. The province's Growth Plan for Northern Ontario (Ontario Ministry of Infrastructure and Ministry of Northern Development, Mines and Forestry, 2011) covers the geographic range of both sub-regions, and proposes actions for further diversification (i.e. enhancing the service sector and increasing value-added manufacturing for raw materials destined for export).

Unlike the other two sub-regions, the economy of Southern Ontario is driven primarily by the service and manufacturing sectors (Hutton, 2010). Predominantly urban (albeit with many rural and agricultural communities on the urban fringe), the economy is influenced in part by provincial legislation supporting the concentration of infrastructure, jobs, and residents, as well as its proximity to trading partners in the United States.

2.0 OVERVIEW OF ONTARIO'S TRANSPORTATION SYSTEM

Ontario's transportation system is extensive, with all four major modes playing important roles in moving people and goods. Figure 2 presents a snapshot of Ontario's transportation system, including principle airports, ports, roads, and rail lines. The following sections introduce and explore each mode in greater depth.

Figure 2: Principle transportation infrastructure in Ontario, including permafrost zones.



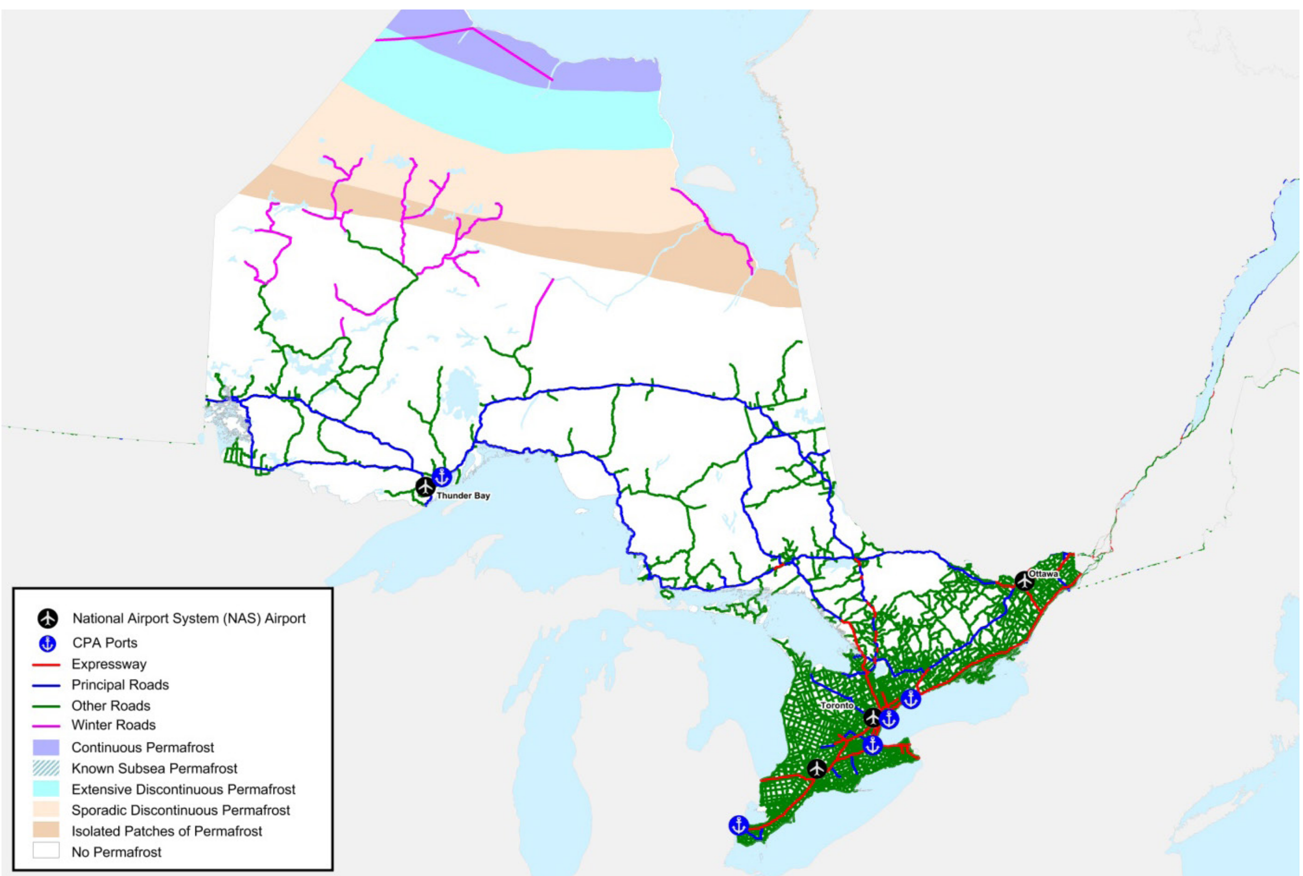
2.1 ROAD TRANSPORTATION

Ontario's highway system includes over 16,600 km of provincially-managed highways, 2,756 bridges, over 1,800 km of the TransCanada Highway system, and an extensive regional/municipal road network (Ontario Ministry of Northern Development and Mines, 2012). There is an extensive user base for this network, which is presented in Figure 3. In 2013, Ontario had over 11 million active road vehicle registrations, including 7.6 million light vehicles (e.g., cars, pickup trucks, and vans) and 237,000 heavy vehicles (e.g., buses and tractor-trailers); the rest of this figure includes trailers, motorcycles, and farm/construction vehicles (Statistics Canada, 2015a).

The road system is an essential component of Canada's international and interprovincial trading network. In 2015, trucking accounted for 68.9 percent of the value of Ontario's trade with the United States (Transport Canada, adapted from Statistics Canada, International Trade database). The Ambassador Bridge border crossing is especially critical, accounting for 23.3 percent of cross-border truck traffic between Canada and the United States in 2015 (Transport Canada, 2016).

Northern and Central Ontario features more than 3,000 km of winter roads, linking remote communities to the provincial highway network (Federal/Provincial/Territorial Sub-Working Group on Northern Transportation, 2015). Ontario's winter roads are built and maintained by 29 First Nations communities and the Town of Moosonee, with financial and technical assistance from provincial and federal governments. While these roads provide only seasonal access (typically from December to March), they are far less costly than constructing all-weather roads on Arctic terrain, which has been estimated at USD$85,000 (CAD$111,758) per road-km and USD$64,000-150,000 (CAD$84,147-197,220)[4] per bridge (Prowse et al, 2009; Dore and Burton, 2001).

Figure 3: Road infrastructure in Ontario.



4 All values related to costs of impacts and adaptations in this chapter are presented in 2015 Canadian dollars. This information was calculated via the Bank of Canada's Inflation Calculator (http://www.bankofcanada.ca/rates/exchange/10-year-converter/).

2.2 RAIL TRANSPORTATION

A number of operators provide rail services in Ontario. Canadian National (CN) and Canadian Pacific (CP) provide freight services within the province, while CN, CP, and CSX (a US company) operate internationally. The most significant commodities moved by rail in Ontario include fuel, metals, chemicals, and manufactured products (Statistics Canada, 2015b).

VIA Rail Canada provides passenger services along the Windsor-Quebec City corridor, from Toronto to Vancouver, and on the Lake Superior route (White River to Sudbury), while Amtrak crosses the border at Niagara Falls and provides service to Toronto. While VIA operates on a 12,500 km rail network, 98 percent of this track is owned and operated by CN, CP, and other partners (VIA Rail, 2015). Ontario Northland also offers freight and passenger services from Cochrane (in the central sub-region) to Moosonee (in the North).

Ontario's rail network also includes:

- 10 local and regional freight operators;
- 11 tourist railways;
- Three light-rail and metro (i.e. subway) systems (Toronto, Ottawa, and Kitchener-Waterloo by 2017); and
- The GO Transit system, providing regional passenger services in Southern Ontario (Railway Association of Canada, 2014).

Metrolinx, a provincial agency responsible for regional transportation planning in the Greater Toronto and Hamilton Area (GTHA), has been upgrading rail throughout Southern Ontario in recent years (Transport Canada, 2014). Notable projects include the Union-Pearson Express, Eglinton Crosstown LRT, and the Regional Express Rail (RER) initiative, a 10-year plan to provide faster and more frequent GO Transit service and electrify core segments of the rail network.

Ontario's rail sector is relatively stable, although operational track-kilometres are declining (Statistics Canada, 2015b). In total, Ontario operated 16 thousand km of track for both freight and passenger services in 2013 – a 15.5 percent decrease from 2009 (Statistics Canada, 2015b). Other recent trends in Ontario's rail sector include:

- Cargo originating in Ontario and destined for other provinces and international markets declined 20 percent from 2001 to 2013 (Statistics Canada, 2015c).
- Goods transported by rail into Ontario from other provinces and North American jurisdictions declined 18 percent from 2001 to 2013 (Statistics Canada, 2015c).
- Passenger movements along VIA's Ontario corridors have declined significantly in recent years, contributing to changes in service patterns (Transport Canada, 2015).
- In contrast, ridership on the GO Transit network increased approximately 28 percent from 2007 to 2013, representing a growing segment of Ontario's commuter market (Metrolinx, 2014).

2.3 MARINE TRANSPORTATION

The Great Lakes and St. Lawrence Seaway (the Seaway) is the most important stretch of navigable water in Canada, encompassing four Great Lakes with Ontario shoreline and the St. Lawrence River. Hundreds of other lakes and rivers in Ontario, particularly in the northern and central sub-regions, also provide shipping, tourism, recreation, and subsistence benefits.

The Seaway is a 3,700-km managed watercourse that became fully navigable in 1959. It operates through a series of locks, and contains other valuable infrastructure (including harbours, and navigation equipment) that enables direct international trade with the United States, Europe, and beyond. Approximately 30,000 tonnes of freight originates in or is destined for Ontario by domestic waterways annually (Statistics Canada, 2010).

The Seaway has historically been a critical path for Prairie exporters shipping grain to eastern markets, with the most important transcontinental transfer and access point to the Great Lakes system located on the north shore of Lake Superior at Thunder Bay (Martin Associates, 2011). Most shipping journeys are significant. A typical route for marine freight running from Thunder Bay to the Port of Montreal is approximately 1,967 km (102 hours of sailing and 17 hours in the locks) (St. Lawrence Seaway Management Corporation, 2014). Important commodities transported through Ontario's segment of the Great Lakes and St. Lawrence Seaway include:

- Agricultural crops (40 percent),
- Mining products (40 percent),
- Iron and steel products (10 percent), and
- "Other" goods, including forestry, animal, and petroleum products (10 percent) (Martin Associates, 2011).

2.4 AIR TRANSPORTATION

Air travel has been gaining importance and market share for both passenger and cargo movement in Ontario. In 2013, 452,000 tonnes of cargo were loaded and unloaded at Ontario's airports (an increase of approximately 5,000 tonnes from 2010), and approximately 45 million passengers passed through Ontario terminals (see Figure 2 for principle airports). Approximately 35 million of these boardings and departures occurred at Toronto's Pearson International Airport, which is Canada's busiest airport (Transport Canada, 2015). Passenger volume in the province has increased by almost 1 million passengers annually since 2010 (Statistics Canada, 2016).

An important influence on the evolution of aviation in Ontario was the 1987 deregulation of Canada's air industry and airport divestiture program. As a result, private interests and quasi-public authorities are now responsible for the capital and operational demands of air infrastructure in many communities (for example, regional airports), although provincial and federal governments continue to contribute significantly to airport infrastructure and upkeep (Transport Canada, 2014). This means that climate adaptation efforts for air infrastructure will involve many levels of government, with a major role for the private sector.

3.0 CLIMATE TRENDS AND PROJECTIONS

This section provides a brief overview of some observed and projected changes in Ontario's climate in order to convey the direction and magnitude of future changes. More detailed information is available from several sources, including the Ontario Centre for Climate Impacts and Adaptation Resources and the Ontario Climate Consortium.

3.1 OBSERVED CLIMATE TRENDS

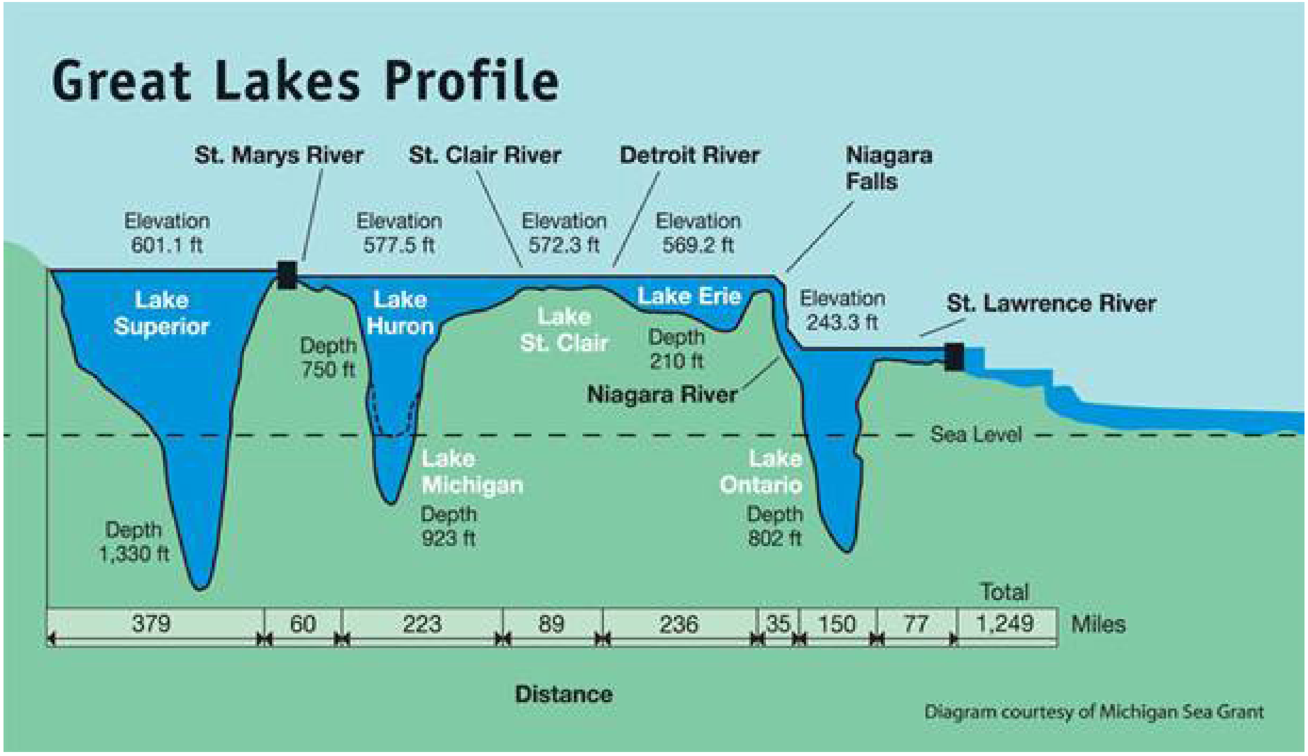
Throughout Ontario, mean annual surface air temperatures have increased by a range of approximately 1.0-1.5°C from 1948 to 2012, while central and northern regions experienced slightly larger increases (Vincent et al., 2015). The greatest warming has occurred in winter. Reflecting these warmer winters, average annual ice cover throughout the Great Lakes declined by 71 percent from 1973 to 2012 (Kahl and Stirrat, 2012).

Annual total precipitation also increased in Ontario from 1948 to 2012, with the most significant increases occurring in the North (Vincent et al., 2015). Snow cover and annual snowfall (as a proportion of precipitation) has decreased in all regions, with the most significant declines in the central and northern sub-regions (Vincent et al., 2015).

It is generally more difficult to recognize changes in extreme weather (i.e. frequency of intense wind, rain, and heat events) than changes in average conditions, although the relationship between increased air temperatures and storm intensity is well-documented (Zwiers and Kharin, 1998; Westra et al., 2015). Analysis in trends of short-duration extreme rainfall for Canada (research including regional and provincial analysis for Ontario) shows that increasing trends are more common than decreasing trends, and that many increases are statistically significant (Shepherd et al., 2014).

The Great Lakes are not considered susceptible to sea level rise, given their respective elevations above sea level (74 metres in the case of Lake Ontario and 183 metres for Lake Superior) coupled with the lakes' outward flow to the Atlantic Ocean (see Figure 4). However, water levels in the Great Lakes are prone to fluctuation. Levels below long-term monthly means were witnessed from 1997 to 2012 (Shlozberg et al, 2014); however, the cold winters of 2013 and 2014 (which featured extensive winter lake-ice coverage and cooler temperatures) broke this trend, with water-level increases in all lakes (Dorling and Hanniman, 2016; Great Lakes Environmental Research Laboratory, 2015). Regardless, the long-term impacts of climate change on water levels will not be clear for some time, as results of the International Upper Great Lakes Study suggest that "natural variability" in Great Lakes water levels may mask the effects of climate change over the next 30 years (Brown et al., 2012).

Figure 4: Profile of Great Lakes' elevations with respect to sea level. (Source: Michigan Sea Grant)



3.2 CLIMATE PROJECTIONS

Ontario's climate is projected to change in all three sub-regions, with some variations. Projected changes in annual and seasonal precipitation and temperature for the province as a whole are shown in Table 2. Figures 5a-b and 6a-b capture sub-regional variation, presenting a gradient of possible changes for the years 2016-2035, 2046-2065, and 2081-2100, in relation to a baseline period of 1986-2005.

Table 2: Seasonal temperature and precipitation projections for Ontario (average provincial values), for three time horizons (2020s, 2050s, and 2080s). Seasonal periods refer to: winter (December-February), spring (March-May), summer (June-August), and fall (September-November). Data was derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate model under an ensemble of RCP2.6, RCP4.5, and RCP8.5 scenarios (Canadian Climate Data and Scenarios, 2015). These data reflect uncertainty associated with these projections by presenting a range of values from the 25th-75th percentiles of CMIP5 outputs. The median value (50th percentile) appears in brackets following the range.

Climate scenario (Representative Concentration Pathway)	Climate variable	Season	Projected change from 1986-2005 baseline (25th- 75th percentiles; 50th percentile in brackets)		
			2020s (2016-2035)	2050s (2046-2065)	2080s (2081-2100)
RCP 2.5 (Low-emissions scenario)	Precipitation (%)	Winter	+0.2-10.8 (+5.3)	+3.2-14.9 (+8.9)	+2.7-13.4 (+7.9)
		Spring	-1.6-+8.4 (+3.7)	+0.7-12.8 (+6.5)	+0.1-11.2 (+5.5)
		Summer	-3.8-+10.8 (+0.5)	-2.6-+14.9 (+2.6)	-3.4-+13.4 (+1.2)
		Fall	-1.4-+8.2 (+3.6)	+0.8-9.7 (+5.0)	+0.2-11.1 (+6.0)
	Temperature (˚C)	Winter	+0.8-1.9 (+1.4)	+1.5-2.8 (+2.2)	+1.4-3.0 (+2.4)
		Spring	+0.7-1.4 (+1.1)	+1.0-2.1 (+1.6)	+0.8-1.9 (+1.4)
		Summer	+0.8-1.5 (+1.1)	+1.0-2.2 (+1.4)	+0.9-2.0 (+1.3)
		Fall	+0.9-1.5 (+1.2)	+1.2-2.5 (+1.7)	+1.0-2.3 (+1.6)
RCP 4.5 (Intermediate-emissions scenario)	Precipitation (%)	Winter	+1.8-11.2 (+5.7)	+7.6-18.2 (+12.9)	+10.0-23.5 (+16.4)
		Spring	-0.9-+10.1 (+3.7)	+3.8-14.2 (8.5)	+4.0-18.8 (+10.7)
		Summer	-4.5-+11.2 (+0.4)	-3.0-18.2 (+2.7)	-2.0-+23.5 (+3.3)
		Fall	-1.6-+9.0 (+3.3)	+3.3-13.2 (+7.8)	+3.1-13.5 (+7.7)
	Temperature (˚C)	Winter	+0.9-2.0 (+1.6)	+2.4-4.1 (+3.2)	+3.1-5.3 (+4.4)
		Spring	+0.6-1.6 (+1.1)	+1.4-2.6 (+2.0)	+1.8-3.7 (+2.5)
		Summer	+0.8-1.4 (+1.1)	+1.6-2.8 (+2.1)	+1.8-3.6 (+2.9)
		Fall	+0.9-1.6 (+1.3)	+1.8-2.9 (+2.2)	+2.4-3.8 (+2.8)
RCP 8.5 (High-emissions scenario)	Precipitation (%)	Winter	+1.6-12.1 (+6.6)	+10.9-23.9 (+17.5)	+21.6-41.7 (+31.8)
		Spring	-0.8-+9.7 (+4.0)	+5.3-21.5 (13.1)	+14.1-36.9 (+24.2)
		Summer	-3.5-+12.1 (+0.7)	-3.8-+23.9 (+1.3)	-8.2-41.7 (-0.5)
		Fall	-1.1-+7.9 (+3.1)	+1.7-13.6 (+7.7)	+6.3-19.9 (+13.6)
	Temperature (˚C)	Winter	+1.2-2.2 (+1.9)	+3.4-5.4 (+4.6)	+6.9-9.7 (+8.2)
		Spring	+0.8-1.7 (+1.2)	+2.3-3.4 (+3.0)	+4.5-6.3 (+5.2)
		Summer	+1.0-1.6 (+1.3)	+2.6-3.9 (+3.1)	+4.7-6.9 (+6.0)
		Fall	+1.1-1.8 (+1.4)	+2.8-4.0 (+3.3)	+4.9-7.0 (+5.8)

Figure 5a: Temperature changes for Ontario in summer (June, July, and August) under RCP 2.5 (low-emissions scenario), RCP 4.5 (intermediate-emissions scenario), and RCP 8.5 (high-emissions scenario) for 2046-2065, as compared to baseline years 1986-2005. (Source: Environment and Climate Change Canada)

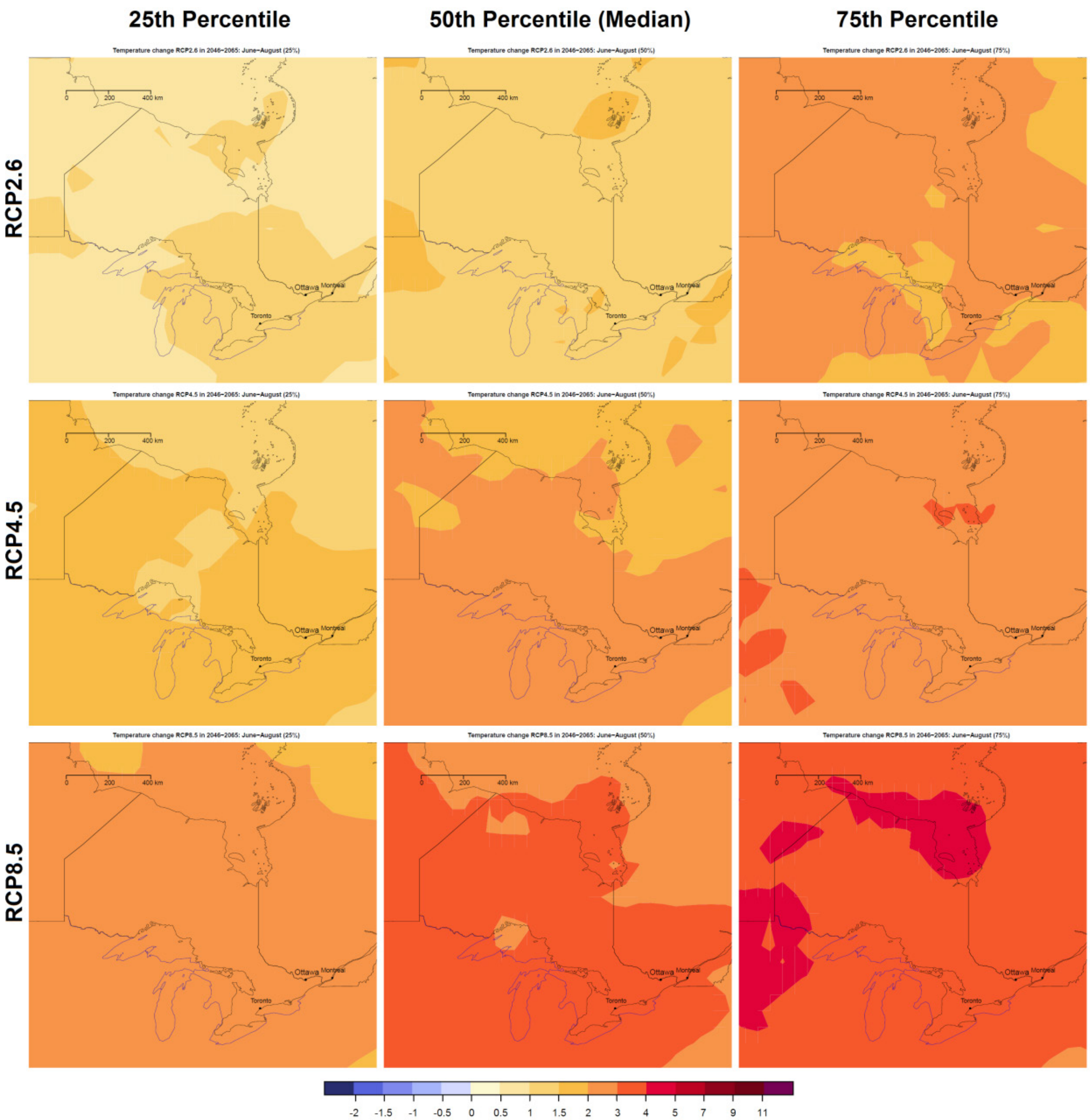
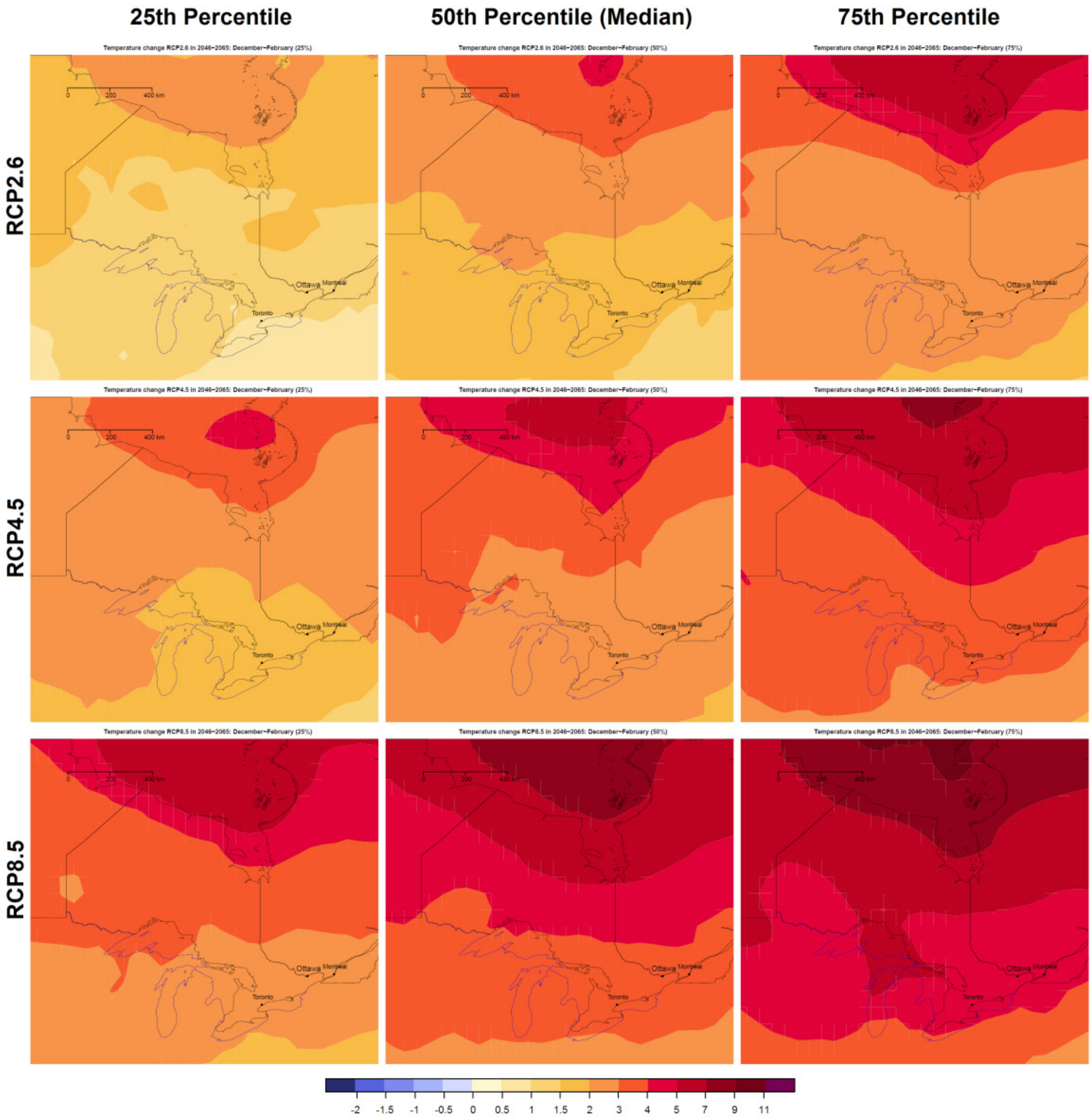


Figure 5b: Temperature changes for Ontario in winter (December, January, and February) under RCP 2.5 (low-emissions scenario), RCP 4.5 (intermediate-emissions scenario), and RCP 8.5 (high-emissions scenario) for 2046-2065, as compared to baseline years 1986-2005. (Source: Environment and Climate Change Canada)



Figures 5a and 5b suggest that warming is projected to continue in all three sub-regions under all future scenarios, with the most drastic increases expected in Northern Ontario during winter. Projected precipitation changes show greater variability, with annual increases in all three sub-regions but seasonal (summer) decreases projected in Central and Southern Ontario under some scenarios. While not captured in the preceding tables and figures, average daily wind speed is projected to increase throughout the province (Cheng et al., 2012b).

In Northern Ontario, snow as a proportion of winter precipitation is likely to decrease, and freezing rain events are expected to increase in frequency by 60-85 percent (Cheng et al., 2007). This creates the potential for road, rail, and runway disruptions and safety issues in Northern Ontario. Warming and thawing of permafrost will most affect the hydrology of peatlands and surface stability in areas where permafrost is currently present (Prowse et al, 2009). Areas along the coast of James Bay and Hudson Bay will experience earlier break-up and delayed freeze-up of sea ice, and will also continue to experience falling relative sea levels throughout this century and beyond, due to a phenomenon known as "isostatic rebound" in which land previously depressed by glaciers rises gradually (Atkinson et al., 2016).

Figure 6a: Precipitation changes for Ontario in summer (June - August) under RCP 2.5 (low-emissions scenario), RCP 4.5 (intermediate-emissions scenario), and RCP 8.5 (high-emissions scenario) for 2046-2065, compared to baseline years 1986-2005. (Source: Environment and Climate Change Canada)

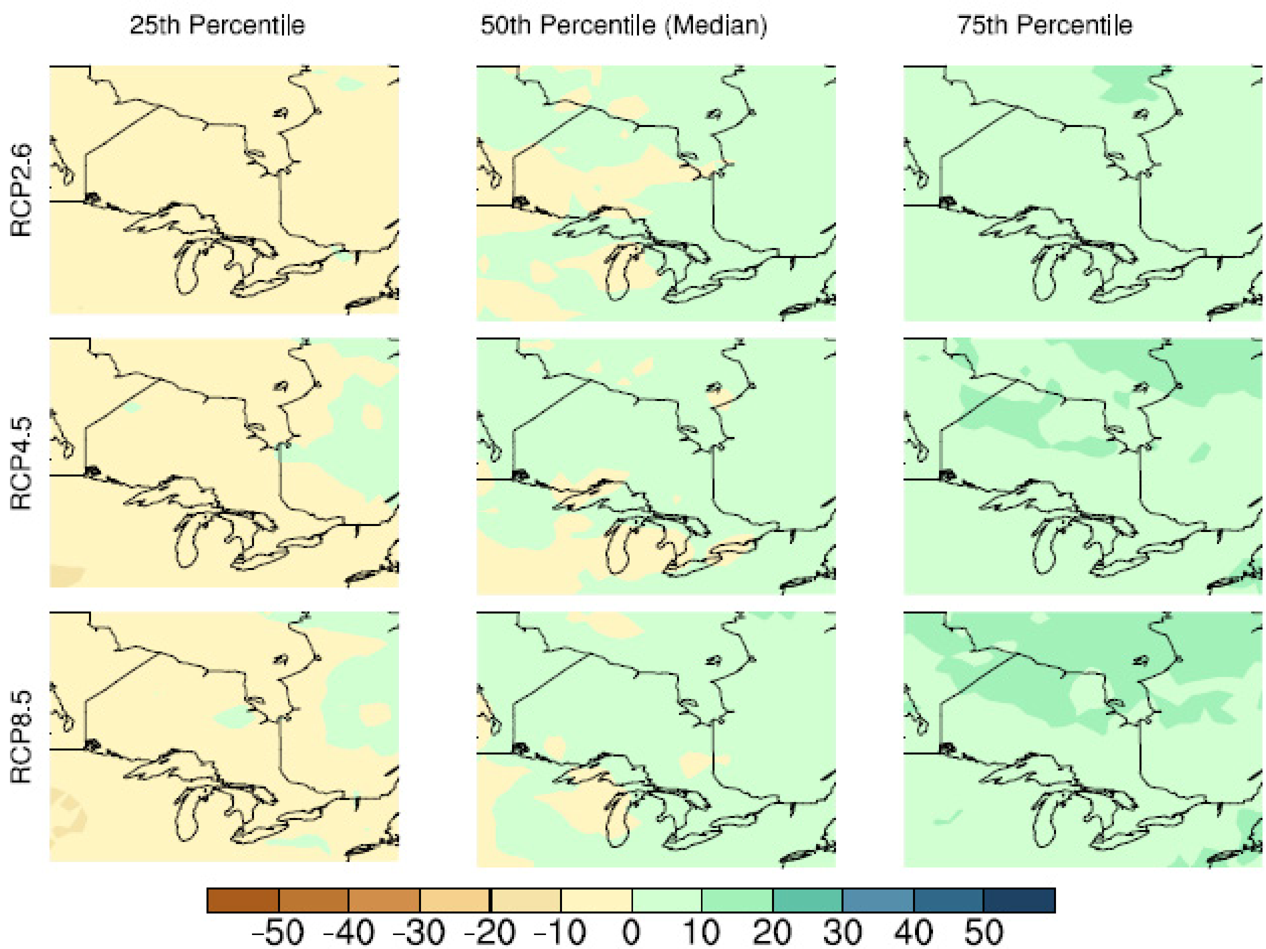
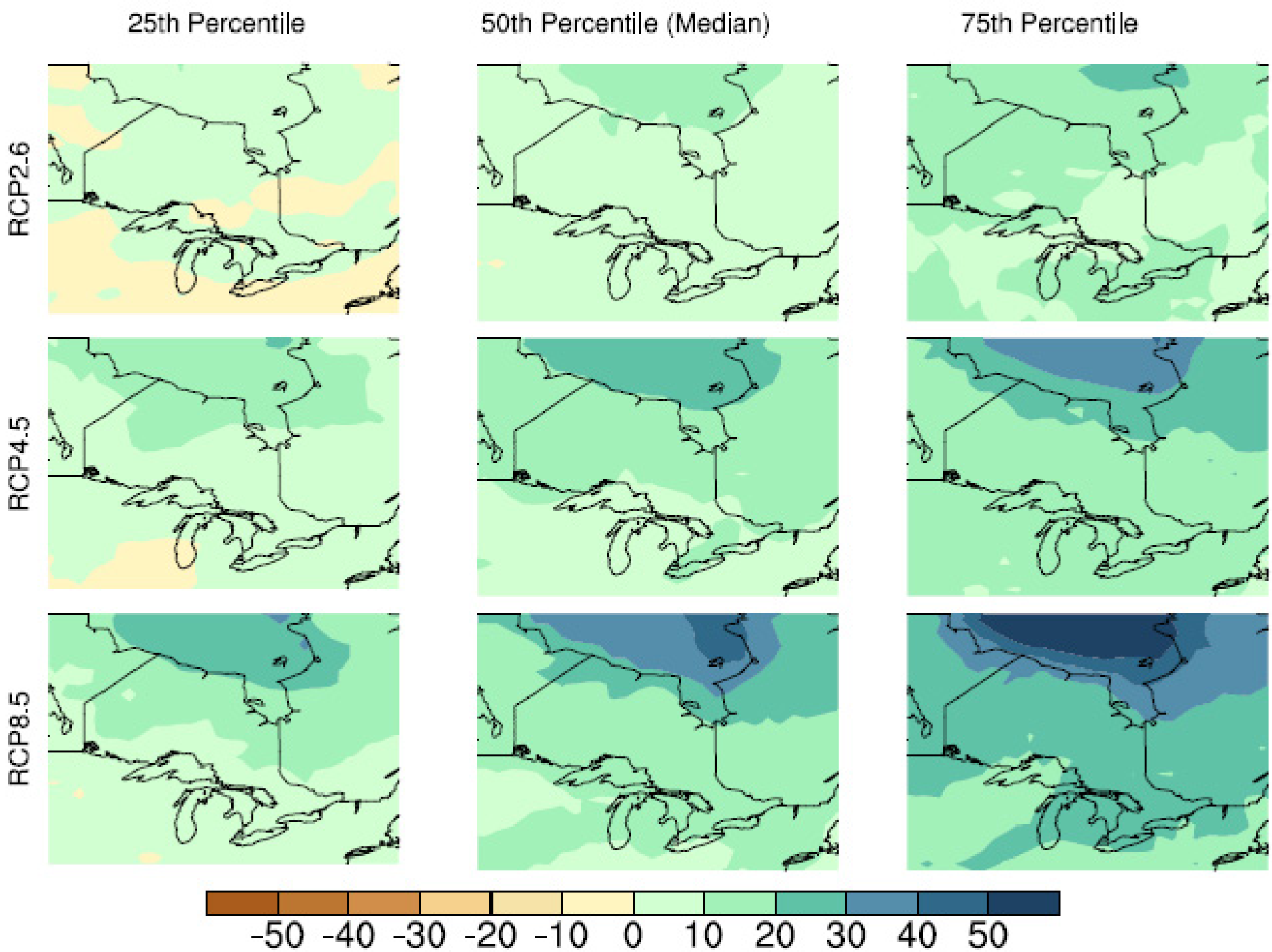


Figure 6b: Precipitation changes for Ontario in winter (December - February) under RCP 2.5 (low-emissions scenario), RCP 4.5 (intermediate-emissions scenario), and RCP 8.5 (high-emissions scenario) for 2046-2065, compared to baseline years 1986-2005. (Source: Environment and Climate Change Canada)



Figures 6a and 6b demonstrate that under most scenarios, precipitation volumes will increase across the province in winter, with more areas experiencing declining precipitation in the summer. In the central and southern sub-regions, the intensity, duration, and frequency of some extreme weather events will likely increase in both summer and winter (Ontario Ministry of Transportation, 2013a; Chiotti and Lavender, 2008; Colombo et al., 2007; Deng et al., 2015). These events include ice storms, heat waves, freezing rain (increasing 40 percent), and intense rainfall (Reid et al, 2007; Cheng et al., 2007). While annual snowfall volumes will likely decline under warmer winter conditions in the next few decades, winter storms may increase in intensity (although decrease in frequency), yielding heavy accumulations of snowfall in singular storm events (Auld et al., 2006). Research focused specifically on Toronto also suggests that while the season in which freeze-thaw events occur (where temperatures fluctuate above and below freezing in a short period of time) may contract, there is likely to be significantly more "freeze-thaw activity" during winter months (Ho and Gough, 2006; Federal Highway Administration, 2015).

The Great Lakes greatly affect regional temperature and precipitation patterns (Gula and Peltier, 2012). Warmer temperatures over the 21st century will likely be associated with a continued decrease in winter ice cover on the Great Lakes, consistent with observed trends (Kahl and Stirrat, 2012), and an increase in lake-effect snow in some locations. Increased temperatures (and evaporation) and a longer ice-free season could lead to water-level decreases of 0.5-1 m in the Great Lakes and St. Lawrence River by 2055 (Shlozberg et al, 2014; Brown et al., 2012). However, long-term future trends toward lower water levels may be overestimated due to the limitations of traditional modeling efforts (MacKay and Seglenieks, 2013). As of February 2015, water levels in Lake Ontario and the St. Lawrence Seaway were 20 cm below monthly historical averages (International St. Lawrence River Board of Control, 2015).

4.0 ROAD TRANSPORTATION IN ONTARIO

4.1 PAST IMPACTS

Historical examples of climate impacts to transportation networks, particularly extreme weather events, can affect public and political perceptions of risk and the likelihood of adaptation action. Major events that have affected transportation in Ontario include Hurricane Hazel in 1954 (Environment Canada, 2013b; see Chapter 9) and the North American Ice Storm of 1998. During the latter event, ice accumulation on electrical infrastructure, roadways, and rail lines caused significant damage and disruption, shut down transportation and signalization networks, and stranded travelers (Environment Canada, 2013b).

In December 2013, another severe winter weather event caused road obstructions throughout Southern and Central Ontario, due to fallen branches, transmission lines, and heavy ice. The City of Toronto (2014) estimates its municipal agencies incurred costs and lost revenue of approximately $106 million as a result of the storm. A number of important adaptive practices were identified following this event, including the need to:

- Improve information-sharing between provincial and municipal governments;
- Enhance coordination between emergency personnel and the infrastructure sector;
- Provide backup power for traffic signals; and
- Update Ontario’s emergency response plan (Office of the Fire Marshal and Emergency Management, 2014).

Recent extreme summer storm events have also caused widespread disruption and damage. In 2002, Northwestern Ontario was struck by intense rain, resulting in $31 million in estimated damages to highways, as well as lengthy closures to TransCanada highways (Chiotti and Lavender, 2008). Damage would likely have been more severe had this storm occurred in a more urbanized area.

The impacts of these events on connectivity are greater for regions dependent on roads and highways with few alternate routes for mobility (such as in Central and Northern Ontario). Washouts from extreme weather events have stranded travelers for extended periods of time in some cases, affecting economic flows and delaying emergency-response personnel.

4.2 FUTURE RISKS

EXTREME AND CHANGING PRECIPITATION

Research suggests Southern Ontario is likely to experience more frequent and severe extreme weather events by late-century (Cheng et al., 2012a). Past impacts of heavy or prolonged precipitation, including flooding and bridge scour in summer, and icy roadways and fallen power lines in winter, have been disruptive to Ontario's roads, bridges, and supporting infrastructure, and similar occurrences pose future risks.

Changing patterns of precipitation will also likely affect Ontario's roads. The province can expect more instances of flooding and washouts as rainstorm frequency increases, which pose safety risks (Boyle et al., 2013). Vehicle accidents are up to 45 percent more likely during severe precipitation events (Andrey et al., 2003). Additionally, freezing rain (as a proportion of winter precipitation) is likely to increase throughout the province (Bruce, 2011; Cheng et al., 2011), creating safety and winter road maintenance challenges (i.e. increased salt and sand requirements).

RISING TEMPERATURES AND EXTREME HEAT

Rising annual temperatures and more frequent extreme heat events have increased instances of pavement softening, rutting, flushing, and bleeding in Southern Ontario in the past (Mills et al., 2009; Woudsma et al., 2007). These impacts are likely to be exacerbated in the future considering projected temperature trends (see Section 3). High temperatures causing thermal expansion of bridge joints ("blow-ups") have also resulted in bridge closures and detours in some jurisdictions (Transportation Research Board, 2008), although the risk of this impact remains low in Ontario.

Warmer winter temperatures and more short-term (i.e. daily) temperature variability are likely to produce more freeze-thaw cycles throughout the province, resulting in pavement deformation and shearing (Boyle et al., 2013; Ho and Gough, 2006). Resulting road damage could interrupt economically important transportation activities, such as heavy-lift/special project cargo movement, logging, and mining, affecting rural communities in Central and Northern Ontario.

Research suggests that while the impacts of climate change on pavement may be modest overall in Southern Ontario, changing conditions should be considered when selecting highway pavement materials (Tighe et al., 2008). For low-volume roads, research indicates that longitudinal cracking and rutting of pavement will worsen as a result of freeze-thaw cycles and extreme heat in the South, while transverse cracking will become less problematic (Mills et al., 2009). Roads will generally require maintenance earlier in their life spans.

Higher temperatures are likely to shorten operating seasons for winter roads in Central and Northern Ontario. For instance, Deloitte (2014) projects that operating windows for winter roads serving Ontario's central and northern First Nations' communities will decline 12 to 20 percent by 2050 from present conditions, and 20 to 40 percent by 2100. Potential socioeconomic consequences include:

- A shorter seasonal window for the movement of freight and people (Deloitte, 2014);
- Higher maintenance costs (Boyle et al., 2013; Transportation Association of Canada, 2010);
- Reduced load capacity (due to decreased ice thickness) (Prowse et al, 2009); and,
- Road embankment failure (Transportation Association of Canada, 2010; Transportation Association of Canada, 2011).

Warmer temperatures also provide some opportunities for Ontario's roads, including:

- Greater fuel efficiency for many vehicles in warmer winters (Maoh et al., 2008);
- Longer construction seasons (Andrey and Mills, 2003); and,
- Reduced winter maintenance requirements (Fu et al., 2009).

CHANGING WATER LEVELS AND ICE PATTERNS

Fluctuating water levels and changing ice patterns in rivers and lakes may also result in roadway flooding. In Ontario, this risk is highest during spring river-ice breakup (Andrey and Mills, 2003). Seiche events (referring to temporary changes in lake levels caused by fluctuating atmospheric pressure) also present flood risks throughout the Great Lakes basin for roads adjacent to bodies of water. More frequent Seiche floods may affect set-back requirements for roads and other critical infrastructure in vulnerable areas over the long term (International Joint Commission, 2014a).

WIND

Wind speeds throughout the province are projected to increase in coming years (Cheng et al., 2012b; Environment Canada, 2014), presenting risks to road transport. Strong winds disperse chemical road treatments; produce drifting snow that reduces visibility, stability, and maneuverability; and damage signals and other tall structures (OFCM, 2002).

4.3 ADAPTATION PRACTICES

PRECIPITATION AND FLOODING

Several practices identified in the literature may reduce the impacts of extreme precipitation on Ontario's roads. These include using alternative routes; conducting risk assessments for new road infrastructure; widening culverts and making other drainage improvements; and conducting more frequent maintenance (Savonis et al., 2008). Some of these practices have been adopted in Ontario: for instance, Toronto has increased regular monitoring and clearing of blocked drainage culverts to address the increased flow of debris (City of Toronto, 2015). The Ontario Ministry of Transportation (MTO) has also undertaken research to update Ontario's intensity, duration, and frequency (IDF) curves to more accurately characterize precipitation in the province, and has assessed the vulnerability of Ontario's highway drainage infrastructure to more severe precipitation events (see Case study 1).

Efficient management and use of de-icing materials (including salt, sand, and brine) reduces the impacts (and associated costs) of freezing rain. For instance, York Region treats rock salt with beet juice to increase its melting capabilities, yielding budget savings of approximately 8 percent annually (Clean Air Partnership, 2012).

Intelligent Transportation Systems (ITS) can also support adaptation on an operational level. Variable message signs can warn motorists of roadway safety concerns in real time to prevent accidents during precipitation events (Andrey and Mills, 2003). Similarly, Ontario's Road Weather Information System (RWIS) (deployed in the 1990s) provides MTO and its contractors with real-time environmental information to inform responsive winter highway maintenance practices (Buchanan and Gwartz, 2005).

CHANGING WATER LEVELS AND ICE PATTERNS (FLOOD RISKS)

In areas particularly vulnerable to flooding, road infrastructure can be relocated or elevated to reduce risks (Savonis et al., 2008). However, elevating roads is costly, and relocation may raise issues related to land expropriation. Therefore, it is often more prudent to enhance the capacity of stormwater management and other flood-prevention infrastructure, such as breakwaters or dykes (Andrey and Mills, 2003).

WIND

To reduce the impacts of wind, structures can be designed to withstand more turbulent conditions (OFCM, 2002). In some rural Ontario communities, living “snow fences” (rows of trees lining open tracts of farmland) have been used to reduce soil loss due to intense wind; however, they also provide co-benefits for transportation by reducing the impacts of blowing snow on roadway visibility in winter (Huron County, 2014).

EXTREME HEAT AND RISING TEMPERATURES

Some parts of the province, including the City of Toronto, use heat-tolerant pavement mixtures to enhance roadway heat-resiliency (Andrey and Mills, 2003; City of Toronto, 2011). The Ontario Ministry of Transportation (MTO) and some Ontario municipalities have also used an asphalt materials characterization system called “SuperPave” since 1997. This system was designed to improve long-term pavement performance (reducing rutting and cracking) under diverse environmental conditions (Ontario Ministry of Transportation, 2013b). The SuperPave system considers high- and low-temperature performance for pavement lifecycles, using detailed weather station data to determine appropriate asphalt mixes for specific locations. While the system does not include projected climate parameters, MTO is implementing an enhanced “mechanistic-empirical” pavement design method for some projects, taking into account pavement performance predictions, detailed weather station data, and traffic levels. The MTO believes this will facilitate the use of road materials and designs that are more responsive to changing climate conditions (Ontario Ministry of Transportation, 2013b).

Finally, reduced seasonal operating seasons for winter roads in Ontario, resulting from warmer temperatures, could require a shift to other modes of transportation (e.g., air) for some shipments, given the prohibitive cost of replacing Ontario’s winter roads with all-weather infrastructure (estimated at approximately $1.5 billion) (Deloitte, 2014). Changes to shipment-scheduling and resource exploration activities have also been proposed as adaptations, along with specific operational and maintenance practices (see Chapter 3 for more detail on these practices) (Prowse et al., 2009; Transportation Association of Canada, 2011).

Table 3 provides an overview of the impacts and adaptations identified in this section.

Table 3: Climate risks, impacts, and adaptation practices for road transportation.

Climate / environmental risk factors	Impacts and opportunities	Adaptation actions
Warmer air temperatures (summer and winter; more variability)	• Increased freeze-thaw cycles • Thermal expansion of bridges, causing detours and traffic disruptions • Pavement rutting, softening, flushing, and bleeding in heat • Reduced operating season/load capacities for winter roads • Longer construction season (opportunity) • Reduced winter road maintenance requirements (opportunity)	• Increase use of road de-icing materials (i.e. salt, sand, brine) • Increase ongoing maintenance • Use more heat-resistant pavement materials (i.e. "SuperPave" technology"); more frequent monitoring/maintenance • Seasonal scheduling adjustments/ modal shift to air for northern shipping
Precipitation (changing seasonal patterns, increasing intensity and extremes)	• Increased likelihood of road washouts and flooding • More extreme rainfall and flooding • More rapid asphalt/concrete deterioration • Increased risk (>45%) of vehicular accidents during heavy precipitation events, especially freezing rain	• Improvements to stormwater management infrastructure • Regular monitoring and clearing of culverts • Change to engineering design criteria to consider higher precipitation volumes • ITS applications, warning motorists of safety hazards; RWIS, informing maintenance activities • Selection of more robust pavement materials • Increase in road de-icing materials (salt, sand, brine)
Changing patterns of lake ice	• Increased risk of flooding, especially from earlier and increased river ice breakup-induced flooding • Shorter winter road operating season	• Investment in flood prevention infrastructure • Modal shift to air transportation
Wind (changes in average wind speeds and extremes)	• Increased runoff from road-treatment chemical dispersion • Loss of visibility, stability, maneuverability in drifting snow; disruptions to signaling equipment and tall structures	• No adaptations identified in the literature • Design structures for more turbulent conditions; "living snow fences" in rural areas
Changing water levels (lakes and rivers)	• Risk of roadway inundation exceeding stormwater capacity of culvert infrastructure	• Relocation or elevation of roadways away from floodplains

CASE STUDY 1

CASE STUDY 1: ASSESSING THE RESILIENCE OF HIGHWAY DRAINAGE INFRASTRUCTURE AT THE ONTARIO MINISTRY OF TRANSPORTATION

There are concerns that an increase in the severity of precipitation events may threaten the future design capacity of Ontario's highway drainage infrastructure. The Ontario Ministry of Transportation (MTO) undertook two interrelated research initiatives to assess this vulnerability and determine appropriate adaptation strategies.

PROJECT 1: UPDATING INTENSITY, DURATION, AND FREQUENCY (IDF) CURVES FOR ONTARIO

This project aimed to update Ontario's intensity, duration, and frequency (IDF) curves to more accurately characterize precipitation in the province.

In partnership with the University of Waterloo, researchers developed IDF curves for all locations in the province. These curves use Environment and Climate Change Canada's most recent historical climate data, and are available via an easy-to-use online platform.[5] The MTO continues to partner with the University of Waterloo to identify trends in the historical rainfall record, which can provide an alternative method of developing future scenarios.

PROJECT 2: ASSESSING HIGHWAY DRAINAGE AND STORMWATER MANAGEMENT INFRASTRUCTURE

This project assessed the resilience of existing highway drainage infrastructure to future precipitation loads, and identified adaptation strategies for a variety of infrastructure components, over their design life.

Researchers sampled two sections of provincial highway, representing different levels of use (Highway 37 near Belleville and Highway 417 near Ottawa). They analyzed the capacity of 25 pipe runs in each section, as well as 46 culverts. The project had three key stages.

Stage 1: Identifying reliable (i.e. likely) precipitation projections under future climate conditions. Based on a review of climate studies in Ontario, and analysis of data, the researchers determined that projected precipitation intensity varies across the province. Accordingly, the researchers considered three climate change scenarios feasible for the infrastructure resilience analysis: 10-, 20-, and 30-percent increases in rainfall intensity. (Note that horizons for change were not defined in this study.)

*Stage 2: Assessing design capacities of sewers and culverts***.** This stage identified the proportion of existing infrastructure that will meet future capacity requirements based on the three precipitation scenarios – that is, the proportion of infrastructure with "hydraulic resilience." While researchers identified minor impacts on sewers for the two sample highway networks, most infrastructure was deemed to possess sufficient capacity for future conditions.

Stage 3: Identifying adaptation measures to alleviate potential drainage issues. This stage required researchers to match adaptations to the risks identified. It was determined that where an increase in the flow velocity presents erosion risks to culverts, more erosion-resistant materials can be used to protect drainage structures. If headwater elevation is a concern, the chosen adaptation will depend on severity. In general, MTO does not allow drainage designs which permit overtopping (i.e. flooding) on Ontario highways; however, if overtopping is unavoidable, twinning existing sewers and culverts to increase capacity is useful.

Bridges are typically designed with limited excess drainage capacity, due to the greater expense of these structures. However, this study determined that precipitation increases up to 30 percent do not pose a threat to bridges. If bridge scour or erosion is likely, physical protection can be provided.

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5 The tool can be found at http://www.mto.gov.on.ca/IDF_Curves/terms.shtml

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SUMMARY

Overall, the results of this study are good news for Ontario highways. It was concluded that MTO's existing design standards for highways are resilient to overtopping within the projected range of precipitation, and increases pose no serious risks to road safety. Specifically, 40 per cent of the pipes demonstrating excess capacity were sized to meet regulatory minimums, rather than to deal with expected rainfall levels. Thus, no infrastructure should need replacing before the end of its lifecycle to account for rainfall increases.

This analysis was limited to possible climate change impacts on the rainfall intensities used in design. Areas that could be considered in future include the impacts of increasing precipitation intensity and duration on foundational materials, and changes to the classification of "regulatory storms" in Ontario (as defined by the Ministry of Natural Resources and Forestry).

Despite these findings, many roads throughout the province remain vulnerable to flood events, including rare occurrences that exceed design capacity. The impact of such disruptions to roads may be reduced via redundancies in the road network (i.e. alternative routes on nearby municipal roads). (See Chapter 9.)

Written in collaboration with Hani Farghaly (Ministry of Transportation Ontario).

5.0 RAIL TRANSPORTATION IN ONTARIO

5.1 PAST IMPACTS

Examples of past climate events resulting in impacts on rail transportation include:

- A July 5-17, 1936 heat wave, exceeding 44˚C in parts of Manitoba and Ontario, resulted in steel rail lines buckling, and bridge girders twisting (Environment Canada, 2013a).
- A December 1942 freezing rain storm in Eastern Ontario coated telephone wires, trees, and railway tracks with thick ice, forcing 50,000 workers in Ottawa to walk to work for five days (Environment Canada, 2013a).
- Hurricane Hazel (1954) caused considerable damage and disruption to rail transportation throughout Southern Ontario (Environment Canada, 2013b).
- The 1998 North American Ice Storm disrupted rail service within and between major cities (Environment Canada, 2013a).
- Severe rain events in 2013 in Toronto flooded rail lines in the Don Valley and in one case stranded GO Transit passengers (CBC News, 2013).

5.2 FUTURE RISKS

Rail transportation faces a variety of unique risks due to changing climate conditions and more extreme weather. Changes to the range of experienced temperatures present challenges for the integrity of rails – this risk is particularly pronounced in Southern Ontario where extreme temperatures will be highest. For example, buckling may occur in extreme heat, increasing travel times (as a result of slower train speeds) and enhancing the potential for derailment, track-sensor malfunction, and hazardous-material spills (OFCM, 2002). High temperatures also result in overheated cargo (Andrey and Mills, 2003). In the North, permafrost thaw weakens rail embankments (Caldwell et al., 2002); in combination with heavy precipitation, washouts and embankment failure may increase in Northern

Ontario (Transportation Association of Canada, 2010). However, warmer winters could reduce cold-weather rail maintenance for Ontario's railways (Andrey et al, 2003).

Wind also poses risks to rail transportation, such as more schedule disruptions and delays; hazardous material spills; railcar blow-over (albeit only during extremely rare events); and disruptions and damage to signalization equipment (OFCM, 2002). Given increasing daily average wind speeds throughout the province (see Section 3), these risks may increase in the 21st century.

More frequent and intense rainfall events may flood rail track, create service disruptions and delays, and reduce on-time performance (Woudsma et al, 2007; OFCM 2002; Koatse and Rietveld, 2012). Rail lines near watercourses are vulnerable to flooding associated with changing water levels and changing patterns of lake ice (Koatse and Rietveld, 2012).

5.3 ADAPTATION PRACTICES

A number of practices to reduce rail vulnerabilities exist in the literature. In the case of extreme heat and rail buckling, approaches include imposing speed restrictions, reducing service frequency, and conducting more frequent track inspections (Savonis et al., 2008). Cargo cooling and refrigeration may reduce product loss and damage for freight carriers (Andrey and Mills, 2003). Researchers have also reported reductions in peak rail temperature by using low-solar absorption rail coatings in sunny conditions (Wang et al., 2015). GO Transit has changed its engineering practices to reduce the vulnerability of its rail to extreme heat (Case study 2).

To reduce infrastructure flooding near watercourses, approaches in the literature include: improving flow management processes, constructing dikes, along with other flood-prevention engineering solutions (Savonis et al, 2008), and elevating track segments (Koatse and Rietveld, 2012). During extreme precipitation events, rail providers may reduce service frequency and increase the timeliness of travel and service advisories (Savonis et al., 2008). Operations can also be modified for forecasted conditions (OFCM, 2002). For example, following various extreme events in the Greater Toronto Area, Metrolinx and GO Transit undertook a number of adaptive measures to enhance rail-corridor resiliency, including:

- Flood-prevention efforts in the Don Valley, installing rail embankment-failure and high-water detectors;
- Service-planning for extreme winter weather (which involves running fewer trains, but reduces the likelihood of delays or cancellations, to ensure business continuity in snowy conditions); and
- The installation of emergency electricity backup at their rail maintenance facility.

Table 4 provides an overview of the impacts and adaptations discussed in this section.

Table 4: Climate risk factors discussed in relation to their impacts on rail transportation. Citations for these impacts and adaptations are located in Section 5.

Climate / environmental risk factors:	Impacts and opportunities	Adaptation actions
Warmer air temperature (summer and winter; more variability)	• Increase in rail buckling events leading to greater potential for derailment and track-sensor malfunction; increased travel time/lesser speed; increased risk of hazard material spills • Overheating of cargo/signalization equipment • Overall reduction in cold-weather rail maintenance requirements (opportunity)	• Speed restrictions, service frequency reductions; air conditioning for signal equipment; inspect tracks more frequently; more timely service advisories and updates • Cargo cooling/refrigeration
Precipitation (changing seasonal patterns, increasing intensity and extremes)	• Flooded; service disruptions and delays; reduced on-time performance during extreme events	• Flood-prevention engineering solutions; increasing travel advisories; modification of operations for forecasted conditions • Embankment-failure and high-water detector installation • Elevation of track
Wind (changes in average wind speeds and extremes)	• Increased schedule disruptions and delays • Increased risk of hazardous material spills • Railcar blow-over • Disruptions to signaling equipment	• No adaptations identified in the literature for this category
Changing water levels (lakes, rivers, ocean)	• Flooding of rails near watercourses	• Construction of dikes; flow management improvements

CASE STUDY 2

CASE STUDY 2: PREPARING FOR HIGHER TEMPERATURES AND RAIL BUCKLING AT GO TRANSIT

Metrolinx is a provincial agency responsible for public transportation in the Greater Toronto and Hamilton Area (GTHA). Its authority extends to capital investments, strategic decision-making, and operational planning for GO Transit (Canada's highest-volume commuter rail and bus service), as well as improving, coordinating, and integrating these services with municipal transit and other modes. Metrolinx and GO Transit have begun to broadly identify threats to the organisation posed by changes in climate and extreme weather events, and to assess vulnerabilities and risks to facilities, practices, and protocols. A corporate climate adaptation policy is also being developed, due to be completed in 2018 (Metrolinx, 2015).

In the near-term, the organisation is responding to the most immediate climate-related concerns with available resources and expertise. These "low-hanging fruit" mainly fall under the operational umbrella, since disruptions to front-line services and road and rail infrastructure pose risks to the quantity and quality of commuter service Metrolinx is able to provide.

For instance, the Railway Corridors division of GO Transit is preparing for the extreme summer temperatures projected for Southern Ontario by the middle of the 21st century. There is a tendency for rail lines to expand and "buckle" in temperatures exceeding 27˚C, which poses risks to operating speed, safety, and line capacity. Minor buckling has been observed along select network segments on hot summer days over the past 10 years. GO engineers have opted to proactively lessen buckling risks to rail lines and service by increasing the preferred rail-laying and rail-distressing temperatures for Southern Ontario from 32.2˚C to 37.8˚C (90 to 100 degrees Fahrenheit). This simple adaptation involves no extra cost – only minor equipment adjustments – yet it has yielded maintenance benefits. Rail buckling has decreased significantly in affected areas since this change was made. While no organisational standards have been changed (largely due to the time and resources required) the practice has been adopted beyond Railway Corridors. For instance, GO Transit is using this higher rail-laying and rail-distressing temperature in the construction of the Union-Pearson Express. This represents an example of a "no-regret" adaptation strategy, referring to actions involving few additional costs, produce co-benefits, or prevent future damage and costs (see Chapter 9).

Practitioners also suggest that updated rail-laying and -distressing temperatures have not significantly affected the tolerance of GO rail infrastructure to colder temperatures. While extreme cold has caused rail contraction in more northern jurisdictions, GO Transit rail lines have not been significantly affected. Practitioners do not expect rail contraction in winter to be as much of a problem in coming decades, given that on average, Southern Ontario is expected to experience warmer winters in the 21st century.

Written in collaboration with Mel White (GO Transit), and Quentin Chiotti (Metrolinx).

6.0 AIR TRANSPORTATION

6.1 PAST IMPACTS

Severe weather, including extreme temperature and storm events, has commonly caused flight delays and cancellations at airports in Ontario. Events affecting one airport can also have a ripple effect, disrupting air travel in other parts of Canada and North America.

For example, from January 5 to 9, 2014, an unusual combination of rain, snow, snow squalls, and wind chills/extreme cold in Eastern Ontario and other parts of Canada severely disrupted passenger travel at many airports, including Toronto Pearson International. Extreme cold (reaching -39°C with wind chill) and ice build-up slowed ground crews and caused some equipment (e.g., fueling) to fail or operate intermittently. The sudden drop in temperature also caused snow and slush, from earlier rain, on taxiways, apron, and gate areas to freeze. Temperatures were too cold for chemical treatments to effectively melt the ice and snow. These operational impacts in tandem with other factors (such as the airport receiving high numbers of diverted flights from other airports), created delays and disruptions in passenger travel throughout Canada. In response to this event, the Greater Toronto Airports Authority (GTAA) reviewed and developed recommendations on the airport's operations, customer service, and communications (GTAA, 2014a).

6.2 FUTURE RISKS

Literature suggests air transportation is affected by a changing climate and extreme weather in several ways. The following climate risks are relevant to airports and aviation in Ontario.

- More variable temperatures increase the risk of ice build-up on wings (GTAA, 2014b).
- Warmer conditions result in decreased air density, which provides less lift for aircraft. This can increase requirements for fuel and runway length (Andrey and Mills, 2003).
- Increased freeze-thaw cycles can cause runway buckling (Transportation Research Board, 2008).
- Extreme cold and heat can affect airplane engines and airport operations, resulting in service delays and reduced on-time performance (OFCM, 2002; Woudsma et al, 2007).
- Thawing permafrost poses a risk to the stability of runways in northern communities dependent upon aviation (Transportation Association of Canada, 2010).
- Flood-prone areas face an increased risk of runway flooding associated with extreme precipitation events and seasonal changes in water levels (Andrey and Mills, 2003; ICAO Secretariat, 2010).
- Greater wind intensity (both daily and during extreme events) increase incidences of foreign objects on runways, taxiways, and maintenance facilities, and impede maintenance of airplanes (especially high on the body, including snow removal and de-icing procedures) (OFCM, 2002).
- Warming temperatures will also lead to more "mixed" precipitation events (for instance, freezing rain combined with snow and rain) during winter operations (GTAA, 2014b).

Airports are also affected by weather events in other areas, since flights may need to be grounded or rerouted, further straining infrastructure and operations.

6.3 ADAPTATION PRACTICES

While air operators in Ontario are already applying some adaptive practices, others could be applied under future conditions. For example, remote airports in Northern Ontario have long used portable forced air heaters to combat ice build-up on aircraft (Transport Canada, 2004). To cope with a projected increase in extreme winter weather and freezing rain events, operators could also adopt changes to engine and wing de-icing procedures in future. This could include a greater use of glycol-based de-icing and anti-icing agents (Transportation Research Board, 2011).

Increasing average temperatures over the long term may also offer benefits to Ontario operators, such as by reducing de-icing requirements in southern locations (Andrey and Mills, 2003). As temperatures increase, however, airports may use more heat-resistant pavement materials for runway construction (similar to asphalt roads) (Andrey and Mills, 2003). Over the longer term, future temperatures may need to be considered when determining runway length requirements.

To enhance the braking and handling ability of aircraft on wet surfaces during periods of heavy precipitation, Ottawa International Airport grooved one of its runways in the summer of 2013. Grooving minimizes the potential for hydroplaning when landing, and construction is relatively non-disruptive. (The runway remained in use during the day while construction was completed over ten nights). After a year of operating on this new surface, pilots reported improved control. The airport then moved forward with plans to groove its longest runway in the summer of 2015 (Schwanz, 2014).

Runways experiencing issues associated with permafrost thaw are common in Northern Canada (Transportation Association of Canada, 2010) (see Chapter 3), although these issues were not identified in literature specific to Ontario. Should permafrost issues arise in future, relevant adaptations include relocating damaged or unusable infrastructure or reconstruction with geosynthetic barriers to enhance stability (Savonis et al., 2008; Transportation Association of Canada, 2010). Thermosyphons – mechanical systems designed to transfer heat from the ground away from infrastructure – also reduce the impacts of thawing permafrost on runways, although the installation costs may be prohibitive for small airports (Transportation Association of Canada, 2010).

Table 5 provides an overview of the impacts and adaptations identified in this section.

Table 5: Climate risk factors discussed in relation to their impacts on air transportation.

Climate /environmental risk factors:	Impacts and benefits	Adaptation actions
Warmer air temperature (summer and winter; more variability)	- More runway length and fuel required due to decreased air density - Delays due to extreme cold and heat (impacts to engines) - Runway buckling	- Consideration of future temperature when determining runway length requirements - Change to engine and wing de-icing procedures (reduced de-icing) - Heat-resistant pavement material selection
Precipitation (changing seasonal patterns, increasing intensity and extremes)	- Service disruptions and delays; reduced on-time performance	- Runway grooving to enhance aircraft braking and handling; reduces risk of hydroplaning
Changing patterns of lake and sea ice	- Increased risk of runway flooding in vulnerable locations	- Improvements in stormwater management infrastructure

Climate /environmental risk factors:	Impacts and benefits	Adaptation actions
Wind (changes in average wind speeds and extremes)	- Increased incidence of foreign objects present on runways, taxiways, and maintenance facilities - Maintenance of airplanes (especially high on the body) impeded - Impeded snow removal/de-icing procedures	- No adaptations identified in literature
Changes in water levels (lakes, rivers, ocean) and patterns of lake and sea ice	- Inundation of airport facilities	- Relocation and flood protection of facilities
Permafrost degradation	- Runway stability issues	- Use of geotextiles for reinforcement; thermosyphons for ground cooling

CASE STUDY 3

CASE STUDY 3: ASSESSING THE VULNERABILITY OF STORMWATER MANAGEMENT INFRASTRUCTURE AT PEARSON INTERNATIONAL AIRPORT

In 2012, the Greater Toronto Airports Authority (GTAA) assessed the vulnerability of selected stormwater infrastructure at Toronto Pearson International Airport to climate change, using Engineers Canada's Public Infrastructure Engineering Vulnerability Committee's (PIEVC) Climate Vulnerability Assessment process. The assessment was chiefly motivated by potential threats to infrastructure under future conditions. These include:

- Flooding of runways, taxiways, and manoeuvring areas;
- Wind damage to terminals and navigational equipment;
- Stormwater runoff exceeding drainage capacity;
- Disruption of operations and ground access; and
- Changing requirements for plane de-icing and snow removal.

The PIEVC protocol gives infrastructure operators a method to assess the vulnerability of their assets in relation to historic, recent, and projected climate parameters. It operates in five stages.

Stage 1 involves project definition. The GTAA chose to focus on selected stormwater infrastructure and the Spring Creek Triple Box Culvert (see Figure 7). The GTAA selected a total of 27 climate variables for impact assessment, including temperature fluctuations, precipitation intensity, duration, and frequency, freeze-thaw cycles, fog, wind, and major storm events, among others (GTAA, 2014b). **Stage 2** involved collecting historical climate data for these variables.

Stage 3 assessed risk. GTAA staff determined risk scores by multiplying the probability of an impact by its severity. According to this assessment, the risk-probabilities of 90 per cent of climate-infrastructure interactions did not increase from current to projected climate conditions. GTAA staff also analyzed 11,640 climate-infrastructure interactions, and 27 per cent scored high enough to merit further technical inquiry.

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In **Stage 4,** the engineering analysis, staff calculated the relationship between current and future climate stress levels and the capacity of stormwater infrastructure. Seven vulnerable interactions were identified, related primarily to heavy, extreme-heavy, and prolonged rainfall events (see GTAA, 2014b for definitions of these events).

Stage 5 identified recommended actions. These included reviewing existing GTAA emergency plans for rain, snow, ice, and high winds; emergency planning for low-probability, high-impact events (e.g., hurricanes and tornadoes); ensuring regular inspection and maintenance of stormwater facilities (despite a generally positive prognosis); and revisiting climate data frequently (i.e. new IPCC scenarios).

Since most assessed facilities were open ponds or very large structures, the analysis concluded that slight temperature and precipitation increases by mid-century (seasonally, annually, and in the frequency and intensity of extremes) will not likely produce serious and specific infrastructure impacts.

Figure 7: Spring Creek Triple Box Culvert at Pearson Airport. (Source: Toronto Pearson - Spring Creek Culvert, 2010 - Photo taken by Morrison Hershfield Limited and provided courtesy of the Greater Toronto Airport Authority)

The PIEVC application suggests that under higher-temperature future conditions, there is a lower likelihood of extreme cold events. However, the probability of high-intensity rainfall events will be greater. During the process, staff became familiar with both extremes – July 2013 brought extreme rain, while December 2013 and January 2014 brought heavy snowfall, significant ice accumulation, and cold temperatures to the region.

GTAA staff suggested that the PIEVC process was useful in identifying both threats and opportunities for airport operations. As a bond-issuing entity, the GTAA has a responsibility to make investors aware of issues that might affect investment decisions, including climate risks. Challenges the GTAA faced when applying the PIEVC protocol included:

- Maintaining consistency and continuity in staff responsible for carrying out the assessment;
- Time- and cost-overruns of approximately 30 percent due to reorganization.
- Ensuring organization-wide buy-in.

Staff suggested that while baseline climate data were somewhat outdated (only historical data for the period 1971-2000 was available; climate normals from 1981-2010 had not yet been released), there was a consensus that more recent data would have shifted trends included in the vulnerability assessment only incrementally.

Overall, the GTAA's PIEVC assessment has raised awareness and understanding of climate risks among operators and shareholders alike. Since the project assessed only $90 million of Pearson's $6-7 billion in assets, the organization is now developing a streamlined process based on the PIEVC model to apply to other infrastructure more rapidly, at a lower cost, and at an appropriate level of detail.

Written in collaboration with Derek Gray (Greater Toronto Airports Authority).

7.0 MARINE TRANSPORTATION IN ONTARIO

7.1 PAST IMPACTS

There are several instances of extreme weather and climate affecting marine operations in Ontario. For example, during the Great Lakes Storm of 1913 (November 7-13), two converging storm fronts created snow squalls and winds of approximately 145 km/h, sinking 34 ships and killing 270 people (Environment Canada, 2013a). The damage, which most affected Lakes Huron, Erie and Ontario, was estimated at $5 million ($119.3 million in 2015 dollars) (Brown, 2002). The nature of Great Lakes navigation during this period increased the risk of ships capsizing, as boats were constructed with the narrow width of the St. Lawrence Seaway and the shallow depth of many Great Lakes tributaries in mind (Catton, 1984). The storm catalyzed boat-hatch and other safety requirements, and ship-to-shore communication technology has since improved significantly, helping to prevent casualties during high-intensity events (Catton, 1984).

Low water levels in the Great Lakes have also negatively affected shippers in the past. In 1964, lower-than-normal water levels damaged harbor infrastructure, requiring $843 million in repairs (in 1988 dollars, or $1.49 billion in 2015 dollars) (Shlozberg et al., 2014).

7.2 FUTURE RISKS

Throughout the 21st century, the Great Lakes will likely experience significant annual warming, greater evaporation, a longer ice-free season, and changing precipitation patterns. These changes will likely affect water levels (see Section 3). For shippers, fluctuating water levels in recent years have affected vessel draft capacities and annual shipping volumes throughout the Great Lakes system. A continuation of this trend would reduce the loads ships can carry (or produce greater variation in seasonal shipping capacity), increase costs, lead to more frequent shipping-schedule disruptions, and reduce shoreline access (Boyle et al., 2013; Shlozberg et al, 2014). Economic losses would be significant. Recent analysis suggests the regional economy would suffer impacts of approximately $1.18 billion by 2030 and $1.92 billion by 2050 as a result of reduced shipping productivity in low-water conditions (Shlozberg et al, 2014). While low water levels are not unprecedented – the 1960s also featured below-average levels in many lakes (Dorling and Hanniman, 2016) – the potential for far-reaching economic impacts make this a key concern for Ontario's economy.

Fluctuations in water levels also affect infrastructure stability, requiring additional dredging of harbour navigational channels and interior facility slips. Such measures carry significant environmental implications. Low water levels can also cause infrastructure decay, as wooden structural elements become increasingly exposed to oxygen (Clark, 2012). Ontario has experienced these issues: low water levels in 2013 caused problems at docks in Tobermory and South Baymouth on Georgian Bay, when ferries sat too low for the fenders (designed to prevent vessels from damaging wharves). Ferry services could not begin as scheduled until these fenders were modified (The Manitoulin Expositor, 2013).

Other risks to marine transportation identified in the literature include flash-flooding of inland waterways as a result of extreme precipitation and overland flow from ice-jams (Andrey and Mills, 2003). High winds during storms also make ship handling more difficult, and ice build-up on structures from more freezing rain and extreme weather events may increase ice-scour damage on dock structures and visual navigational aids during winter (OFCM, 2002).

Practitioners also suggest that "seasonal shift" of the navigable period is another important issue for shippers in the Great Lakes and St. Lawrence Seaway, pushing traditional construction and maintenance schedules out of alignment with operational demands. For instance, extended or year-round shipping in the Great Lakes would shorten or eliminate the "lay-up" period for operators in the Great Lakes, when fleet maintenance and preparation typically occurs.

Seiche impacts (which result from temporary changes in lake levels caused by fluctuating atmospheric pressure) also pose significant risks to marine infrastructure and operations in the Great Lakes. For instance, a recent Seiche event in Lake Michigan changed water levels by more than 3 metres in under an hour, leaving marinas completely dry before flooding them suddenly, destroying vessels and infrastructure (International Joint Commission, 2014a).

The changing climate also creates opportunities for the marine transportation sector. These include:

- A longer float plane season in some areas of the province (Andrey and Mills, 2003) (most notably the central and northern sub-regions in Ontario);
- A longer spring and summer shipping season;
- Less ice accumulation on vessels and rigging (Transportation Research Board, 2008); and,
- Possible new shipping routes (including the potential opening of shipping routes through the Arctic, although these face limitations – see Section 2.4) (Prowse et al, 2009).

7.3 ADAPTATION PRACTICES

A number of adaptations for marine transportation are identified in the literature. In cases where lower water levels affect navigability, shippers may shift freight to road or rail (Savonis et al., 2008). Other responses to lower inland water levels include changing navigation procedures; investing in flow augmentation technologies; and increasing dredging of channels (Andrey and Mills, 2003). The St. Lawrence Seaway Management Corporation (SLSMC) is taking an adaptive management approach to changes in climate, which includes monitoring water levels and ice patterns (see Case study 4). Commercial shippers operating in the Great Lakes also possess a degree of adaptive capacity and flexibility; operators take water levels into account when loading vessels, typically three to four weeks before arriving in Canadian waters (for international transits).

A cost-benefit analysis of flow-regulation alternatives for portions of the St. Lawrence Seaway found that the most cost-effective solution involves constructing a series of sills, or speed bump-like structures, in the Upper St. Clair River that would reduce the speed at which the river flows. This would yield net economic benefits upwards of $250 million (Dorling and Hanniman, 2016). *Plan 2014*, a flow-management plan for Lake Ontario and the Seaway developed by the International Joint Commission (2014b), aims to reduce damages for property owners, including ports and harbours by controlling the possible range of water levels. Largely, these planning initiatives attempt to reduce the risks associated with uncertain future water levels (International Joint Commission, 2014b; Dorling and Hanniman, 2016).

E-Navigation (electronic navigation) refers to modern navigation technologies and services that may help operators adapt to periods of lower water levels in Ontario. Potential improvements to these systems include establishing internet connections to provide basic ship-to-shore communication channels along navigable waterways. Modern "under-keel optimization systems" have also been implemented in some locations between Quebec City and Montreal along the St. Lawrence Seaway (Canadian Coast Guard, 2015), allowing operators to adjust speed (and draft) in order to pass through constrained channels, better managing the risks of fluctuating water levels (Galor, 2007). This system has also been proposed for parts of the Seaway passing through Ontario, including the St Clair-Detroit River, and the St. Mary's River.

Addressing the possibility of ice-jam flooding during early spring thaws, may require more frequent use of ice-breaking vessels. Practitioners in Ontario suggest that the past two winters have demonstrated the need to account for increased hours of operation for these vessels. For ports at risk of flooding (such as in those on the Great Lakes vulnerable to Seiche events), investments in some flood-proofing infrastructure (i.e. breakwaters and dikes) may be prudent (Savonis et al., 2008).

In some parts of the province, ice blowing into locks delays the opening of the navigation season. This impact may be reduced by using ice curtains (which restrict ice moving into locks) and air bubblers (including compressors and fuel). However, as ice cover decreases throughout the 21st century, issues posed by ice breakup should become less problematic for operators.

Table 6 provides an overview of the impacts and adaptations identified in this section.

Table 6: Climate risk factors discussed in relation to their impacts on marine transportation.

Climate/environmental risk factors:	Impacts and benefits	Adaptation actions
Warmer air temperature (summer and winter; more variability)	• Lower water levels on fresh-water navigable watercourses (i.e. Great Lakes), leading to increased costs/more trips • Reduced ice accumulation on vessels and rigging (opportunity) • Longer shipping season due to longer ice-free period (opportunity)	• Changes to navigation procedures; channel dredging; flow augmentation
Precipitation (changing seasonal patterns, increasing intensity and extremes)	• Disruption to shipping schedules • Flash-flooding of inland waterways	• Seasonal shift in shipping practices • Flow management improvements
Changing patterns of lake and sea ice	• Increased shipping hazards due to longer period of ice pack weakness (ex. increased wave action, storm surge, etc.) • Lengthened summer shipping season, emergence of new shipping routes (opportunity) • Lengthened season for use of float planes (opportunity)	• Greater investment in ice-management equipment and resources
Wind (changes in average wind speeds and extremes)	• Short-term water level fluctuations from sustained winds (Shlozberg et al, 2014) • Increased difficulty of ship handling	• No adaptations identified in the literature • No adaptations identified in the literature
Changes in water levels (lakes, rivers, ocean)	• Seiche flood events • Decreased shipping capacity in GLSLS; more frequently-restricted channels • More difficult access to shoreline marine infrastructure • Port flooding and infrastructure damage from storm surges	• Relocation/flood-proofing of port infrastructure • Modal shift of freight to road, rail, and air • E-Nav and "under-keel optimization" technologies • Increased dredging of channels • Investment in flood-proofing at technologies (i.e. breakwaters and dikes)

CASE STUDY 4

CASE STUDY 4: WATER LEVELS, ICE REMOVAL, AND ADAPTIVE MANAGEMENT AT THE ST. LAWRENCE SEAWAY MANAGEMENT CORPORATION

A changing climate is likely to produce significant impacts for transportation operators in the Great Lakes-St. Lawrence Seaway. The Seaway is an important international marine shipping route spanning 3,700 km over many jurisdictions. Critical stretches include the Welland Canal (connecting Lakes Ontario and Erie) and the segment from Lake Ontario to Montreal. The St. Lawrence Seaway Management Corporation (SLSMC) is the Canadian agency responsible for ensuring marine traffic moves safely and efficiently through 13 of the waterway's 15 locks.

There is much uncertainty regarding water levels throughout the Seaway, as they tend to vary year-to-year. Some studies suggest lower water levels will be the norm through the 21st century (Shlozberg et al., 2014). Other studies suggest that increased precipitation may cause periodic fluctuations in these levels (MacKay and Seglenieks, 2013). Either way, strategies to deal with uncertainty are recommended. For shippers, lower water levels pose risks to shipping capacity and efficiency, reducing the volume of freight that can be moved. Andrey et al. (2014) suggests that for each centimetre of water lost, the capacity of an average ship decreases by six containers (60 tons).

Over the short-term, significant ice formation has been problematic for shippers and infrastructure operators in the Seaway, including the SLSMC. Ice build-up delays seasonal opening and increases removal, break-up, and flushing requirements. While flow-management infrastructure upgrades are considered too costly and difficult to implement (Andrey et al, 2014), the SLSMC has adopted a number of adaptive procedures in light of observed and projected impacts.

For instance, the SLSMC collects extensive climate data to determine how environmental conditions will affect infrastructure performance over the short and long term. It also monitors water levels, temperature and wind conditions, and ice patterns. The organization uses this data to predict seasonal Seaway opening and closing dates, secure requisite ice-breaking services and assets, and rent an appropriate volume of ice-management equipment for channels and locks.

However, practitioners have observed increased variability in weather along the Seaway in recent years, making it difficult for the SLSMC to accurately predict opening and closing conditions and associated processes. During the navigation season, the SLSMC has procedures to deal with extreme (short-term) events, including wind causing low water levels. These include:

- Suspending navigation and temporarily redirecting vulnerable vessels to safe anchorage areas until conditions become acceptable again.
- Activating "no-meet zones" when required (prohibiting two-way marine traffic),
- Restricting speed and draft to reduce navigational risks (i.e. striking bottom).

Reduced maximum permissible shipping draft[6] is an especially problematic impact of declining water levels, since the costs of reduced efficiency are transferred to shippers and businesses further down the supply chain. To increase safety for deep-draft vessels, many vessels have installed onboard Draft Information Systems. This software application provides graphical representations of the anticipated under-keel conditions for a vessel given its position, speed, and heading in relation to surrounding water levels and bathymetry. The system allows vessels to take proactive, draft-altering measures to ensure safe transit by adjusting speeds. In 2014, 39 inland commercial ships used this application in the Seaway, though there is potential for greater uptake.

Ice is another major consideration for the SLSMC, and caused delays opening the Montreal-Lake Ontario Seaway section in 2014, increasing removal, break-up, and flushing requirements. Ice management

6 Draft refers to the vertical distance between the waterline and the bottom of a ship's hull. This affects the depth of a ship in the water.

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depends heavily on coordination with the Canadian and U.S. Coast Guards for support from their ice-breaking vessels. The SLSMC also contracts tugboats with scrapers and excavators for ice management when needed.

Ice does not typically delay opening of the Welland Canal. However, at the beginning of the 2014 season, ships travelling through the passage from St. Catharines to Port Colborne had nowhere to go because of ice on Lakes Erie, Superior, and Huron. Ice was also blown into locks, causing temporary delays.

Ice is a more significant concern from Lake Ontario to Montreal, due to greater geographic diversity and more severe conditions overall. Ice curtains and air bubblers are used to keep locks free from ice where and when it is feasible to do so. Increasing ice-management capacity has proven useful for adapting to changing patterns of winter weather extremes, but may become less costly as winters gradually warm throughout the Seaway.

Written in collaboration with Shari Grady (St. Lawrence Seaway Management Corporation).

8.0 A MULTI-MODAL APPROACH TO TRANSPORTATION AND ADAPTATION

A changing climate will affect Central and Northern Ontario differently than the South, and adaptive capacity varies considerably among municipalities within these sub-regions. Compared to the South, these two sub-regions encompass a larger area, and have fewer data and resources available to support adaptive decision-making for transportation (Chiotti and Lavender, 2008). The provincial government has taken steps to determine appropriate climate adaptation strategies for transportation in these regions, and has initiated a multimodal study of Ontario's "near north" and "far north" (approximating the central and northern sub-regions) (Caroline De Groot, Ministry of Transportation of Ontario, personal communication, 2015).

This study will identify short-, medium-, and long-term improvements for all modes of transportation. It will also provide transportation users and service-providers with tangible adaptation solutions and decision-makers with a foundation for action, by identifying:

- Strong analytical evidence (i.e. rigorous, scientific climate data) to support anecdotal evidence of climate change (i.e. shorter winter-road access seasons);
- Possible effects of climate change on Northern Ontario's construction, operations, and maintenance standards for roads, railways, airports, and marine infrastructure; and,
- Best-practice alternatives and strategic directions to address the challenges mentioned above.

9.0 KNOWLEDGE GAPS AND CONSTRAINTS TO ADAPTIVE DECISION-MAKING IN ONTARIO

Despite progress on a number of initiatives in the province, barriers to adaptation in the transportation sector persist. Limited resources and expertise can be are obstacles to developing and implementing meaningful adaptation strategies, particularly in Central and Northern Ontario.

The cumulative impacts of climate change on transportation infrastructure, referring to two or more simultaneous impacts, are understudied and difficult to predict. For instance, increasing numbers of freeze-thaw cycles in Ontario may combine with non-traditional, mid-winter flood events exceeding stormwater thresholds, creating destructive lifting and shearing forces on highways, bridges, locks, and harbours, with potentially costly and damaging effects. While concrete examples of these impacts are lacking in Ontario, recent winter storm events in the United States and United Kingdom suggest that infrastructure damage resulting from flooding on frozen ground may be severe (Oh et al., 2010; Met Office, 2014).

Treating adaptation as an issue separate from other aspects of transportation is an additional constraint. Communities and practitioners in Canada have not yet integrated adaptation goals into much of their transportation planning and decision-making (Newman et al., 2013; Henstra, 2015). Some initiatives in Ontario, such as those highlighted in case studies, represent noteworthy exceptions.

Constraints also exist within the climate science and adaptation community, the transportation sector (broadly considered), and the integration of efforts across these two fields. The variety and complexity of available climate model data makes it difficult for decision-makers to assess vulnerability and determine appropriate adaptation options. Engineers Canada (2012) also argues that a lack of localized climate projections makes it difficult for decision-makers to justify investing in more expensive adaptive infrastructure over cheaper infrastructure, which is typically designed for historic climate pressures (often with the use of outdated data). Remedies to this situation include maintaining and developing more robust historical records and climate modeling processes, and training engineers in dealing effectively with climate uncertainty.

A further challenge is the traditional complexity of the freight system and different jurisdictional responsibilities. Considering the range of actors and agencies at play in international road freight activity, it is often difficult to determine how to undertake climate adaptation, and who is responsible.

10.0 CONCLUSIONS

Ontario faces diverse and potentially costly risks associated with changing climate conditions and evolving transportation requirements. While Ontario's adaptive capacity is generally high, vulnerabilities to extreme weather and gradual changes in climate present challenges to transportation decision-makers and infrastructure operators.

The adaptation practices described in this chapter speak to the willingness of decision makers to confront the risks to efficiency and safety posed by a changing climate to both infrastructure and operations. The challenge at all levels is to provide coordinated, timely, and effective responses to these risks.

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7 · Quebec

CHAPTER 7: QUEBEC

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KEY FINDINGS

- **Climate change will affect the natural environment of all regions of Quebec and may damage or cause service interruptions to transportation systems**. Nunavik has, and will continue to, experience significant climate change and will have to deal with the thawing of the permafrost on which transportation infrastructure is built. In eastern Quebec, the increase in relative sea level, loss of ice cover, freeze-thaw cycles and changes to storm systems will contribute to further erosion of riverbanks and shorelines. For all regions of Quebec, Surface runoff management is a challenge.

- **The vulnerability of transportation systems to climate change varies according to regional characteristics, the type of infrastructure and its use.** The condition and maintenance of infrastructure, the current use of transportation systems and the availability of alternatives during service interruptions, are all factors that influence the scope of climate change impacts on transportation systems.

- **Extreme weather events represent one of the greatest risks for the transportation sector, in all the regions of Quebec.** Episodes of heavy rain, floods, coastal erosion and landslides will affect both the transportation infrastructure and the mobility of people and goods. The isolation of communities that depend more on one particular mode of transportation could be accentuated by extreme weather events.

- **Although thawing permafrost is the most significant climate change impact affecting Quebec's northern communities, similar to the northern territories, rising temperatures are also reducing winter mobility due to shorter freezing periods.** The shorter winter season and loss of ice cover make access to the region and its resources more difficult for individuals who depend on them for their way of life.

- **Climate change adaptation issues represent significant social, institutional, environmental and economic challenges.** Success stories in this area are the result of multisectoral initiatives, involving players from the public and private sectors and civil society, and their inclusion in existing planning efforts.

- **Acquiring data to monitor the condition of infrastructure and efforts to search for effective solutions for transportation systems are key means of adapting to the inevitable changes.** Adaptation options will affect both the design and management practices for the operation and maintenance of infrastructure. Analysing the potential performance of these options depends on a solid knowledge of the transportation systems and the environment in which they operate.

1.0 INTRODUCTION

In Quebec, transportation plays a major role in supporting the vitality of regions, the distribution of goods and services, and the exploitation of natural resources. Most transportation infrastructure (road, rail, marine and air) was designed with a stable climate in mind, but climate change is affecting both the lifespan and condition of the infrastructure. The size of the province, the remote nature of certain Quebec communities, and the limited redundancy of the transportation system,[4] in the regions most affected by climate change, are also factors that increase its vulnerability.

For nearly 20 years, the Quebec government, carrier associations, expert panels, and companies have been making greater efforts to adapt transportation systems to climate change and thus strengthen its resilience. These efforts have enhanced knowledge about the impacts and potential solutions to improve the management of transportation infrastructure.

This chapter describes the organization of transportation in Quebec by mode and by region, and identifies its main vulnerabilities to climate change, based on existing literature and studies. The chapter also identifies adaptation practices that could be used to address these challenges.

1.1 REGIONAL PROFILE

DEMOGRAPHICS AND SOCIO-ECONOMIC CONTEXT

Quebec covers more than 1.6M km^2 (Institut de la statistique du Québec, 2014) and has approximately 8,263,600 residents (Institut de la statistique du Québec, 2015; see Figure 1), making this province the second most populated in the country. More than half (60%) of the Quebec population is concentrated in an area 10 km wide on either side of the St. Lawrence river (Institut de la statistique du Québec, 2014).

More specifically, the Quebec population is concentrated in a few large urban areas in the southern part of the province (Montréal, Québec City, Gatineau, Sherbrooke, Trois-Rivières). In other regions, the population is more dispersed. For example, Nunavik makes up a little less than one-third of the territory and has approximately 12,700 residents in 14 northern villages and the Cree community of Whapmagoostui.

Population growth is expected in 13 of the 17 administrative regions of Quebec by 2061 (Girard, B-Charbonneau and F-Payeur, 2014). The regions which are expected to see this population growth will be those supported by international migration (Montréal and Laval), inter-regional migration (Outaouais), internal migration (Laval, Lanaudière), and a rising fertility rate (Nunavik).

As shown in Table 1, the urban areas of the National Capital,[5] Montréal, Montérégie, Laval and the Outaouais are characterized by their significant industrial diversity, and account for 67.4% of the Gross Domestic Product (GDP). The proximity of these areas to waterways and international transportation infrastructure is vital to their success. Other regions depend more on the extraction of raw materials or tourism. The area of the gulf and estuary of the St. Lawrence is home to close to 5% of Quebec's population and accounts for a similar share of the province's economy (Beaulieu, 2014).

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4 The redundancy of a transportation system refers to the alternatives the system provides, ensuring additional routes and services if the first option is disrupted. A system with little redundancy provides few options.

5 Québec City region

Table 1: Population distribution and economic activity by region. (Source: Soucy, 2015)

Administrative Region	Population (2014)	Demographic Weight	Land Area	Density	Economic Weight
	Residents	%	KM²	Res/KM²	%
01 Bas-Saint-Laurent	200,292	2.4	22,154	9.0	2.0
02 Sagueneay-Lac-Saint-Jean	277,786	3.4	95,870	2.9	3.2
03 Capitale-Nationale	731,838	8.9	18,663	39.3	10.0
04 Mauricie	266,794	3.2	35,531	7.5	2.5
05 Estrie	320,008	3.9	10,193	31.4	3.2
06 Montréal	1,988,243	24.2	500	3,992.5	34.6
07 Outaouais	383,182	4.7	30,331	12.6	3.6
08 Abitibi-Témiscamingue	147,868	1.8	57,550	2.6	2.1
09 Côté-Nord	94,906	1.2	235,582	0.4	2.3
10 Nord-du-Québec	44,256	0.5	697,152	0.1	0.9
11 Gaspésie-Îles-de-la-Madeleine	92,472	1.1	20,327	4.6	0.8
12 Chaudlières-Appalaches	419,755	5.1	15,001	27.8	4.2
13 Laval	420,870	5.1	246	1,710.9	4.1
14 Lanaudière	492,234	6.0	12,299	40.0	3.6
15 Laurentides	586,051	7.1	20,490	28.5	5.4
16 Montérégie	1,508,127	18.4	11,141	135.7	15.1
17 Centre-du-Québec	239,990	2.9	6,899	34.7	2.6
All of Quebec	8,214,672	100	1,300,815	6.3	100

2.0 ORGANIZATION OF TRANSPORTATION IN QUEBEC

The transportation of goods and people in Quebec is multimodal and interconnected (CPCS, 2013). While trucking is the preferred mode for transporting goods; railways and waterways that connect the St. Lawrence to the Great Lakes, also play an important role. Air transport, meanwhile, carries a lesser volume of goods, but remains a strategic mode when delivery must be done quickly and the weight of the goods is not an issue (CPCS, 2013: 2-29).

In Canada, the St. Lawrence is a key continental gateway. This multimodal axis of transportation is strategic for the economy, demographics and geography of the country, making Quebec a hub for the transportation of goods to other provinces and to the United States. The Quebec-Windsor corridor concentrates approximately 80% of the activities of VIA Rail Canada (2014). The St. Lawrence drainage basin, which includes the Great Lakes, is the largest drainage system in the world, draining more than one quarter of the world's fresh water reserves (Institut de la statistique du Québec, 2014).

Other regions of Quebec are connected to the southern part of the province by strategic corridors that allow for the exploitation of resources, such as forests, hydroelectricity and minerals. These regions depend primarily on roads for the transportation of goods and people. There are also air connections for each of these regions. The size of the area and the dispersed population result in major challenges in planning and managing transportation networks (Ministère des Transports du Québec, 2013a).

Finally, the 14 Inuit communities and the Cree community of Whapmagoostui in Nunavik are only accessible from the southern part of the province by air or sea, as are the Magdalen Islands and certain communities located in the far eastern portion of the lower North Shore.

In Quebec, the planning, design, and management of transportation infrastructure; as well as construction, repair and maintenance work, are the responsibility of several institutional and private partners. Various Quebec government departments, public transportation agencies, public transit agencies, federal government departments and agencies, carrier associations, inter-municipal councils and municipal transportation agencies, local municipalities, regional county municipalities, metropolitan communities and First Nations communities are all involved to varying degrees.

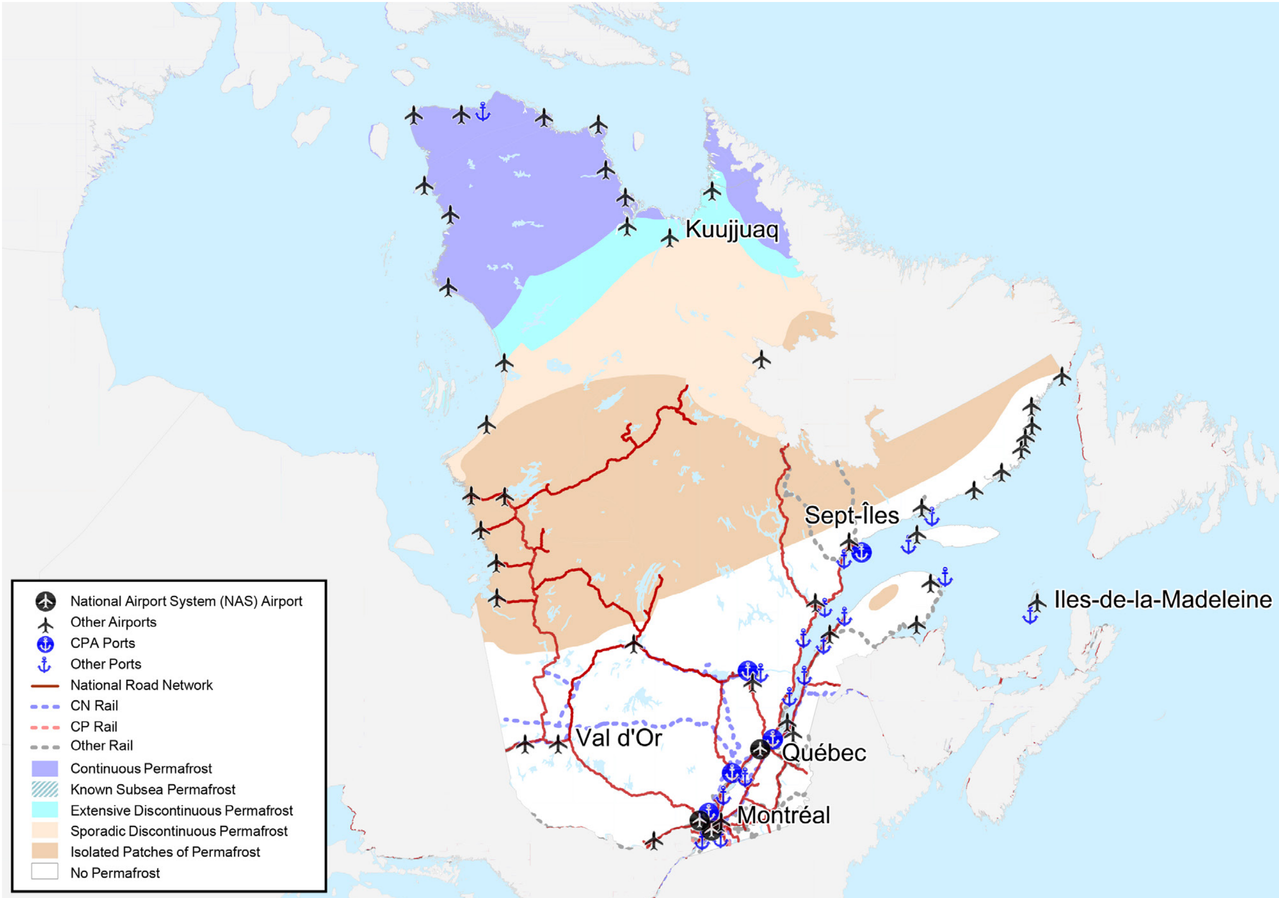
Quebec's Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDET) plays a central role in the management and sharing of responsibilities for transportation infrastructure. Highways; national, regional and collector roads; and some access roads to remote resources and communities fall under Quebec's jurisdiction (Ministère des Transports du Québec, 2015b). The MTMDET shares the management of these networks with carriers and private operators, as well as some local and regional authorities.[6] The main railway networks are primarily under federal jurisdiction, but are also under provincial jurisdiction (short lines), as well as under the responsibility of a dozen private organizations, or large railway companies such as Canadian National (CN) or Canadian Pacific (CP). Quebec ports and airports are owned and managed by a wide range of public and private stakeholders.

Furthermore, the MTMDET produces manuals and guides to direct the design, management and maintenance of transportation structures and systems. These manuals are used as the main reference guide by Quebec municipalities for roads under their responsibility.

Figure 1 presents Quebec transportation infrastructure and shows the diversity of the main infrastructure in Quebec and the many organizations that share in its management.

6 The Société de développement de la Baie-James (SDBJ) for the James Bay road network owned by Hydro-Québec, and the Kativik Regional Government for the Nunavik airports.

Figure 1: Map of principle transportation infrastructure in Quebec.



The Quebec-Ontario Continental Gateway and Trade Corridor initiative was undertaken jointly by the Quebec, Ontario and Canadian governments in 2007. It aimed to create an integrated multimodal transportation system that was reliable, sustainable and competitive to support international trade. In this respect, the St. Lawrence valley can be considered the main corridor in Quebec's transportation infrastructure network, and provides for much of the exchange between Quebec and its main economic partners. It includes the major urban hubs of Montréal and Québec City. Figure 2 illustrates this intermodality across Quebec.

Figure 2: Intermodal hubs in Quebec. (Source: Gouvernement du Québec, ministère des Transports, 2013 (data from 2010))

2.1 ROAD TRANSPORTATION

Road transportation is one of the most flexible and accessible modes and is proving to be the preferred mode for short-distance, inter-regional and inter-provincial transportation of goods and people (Ministère des transports du Québec, 2013b). In addition to ensuring access to much of Quebec, road infrastructure facilitates intermodal connections with rail terminals, ports and airports (CPCS, 2013).

There are approximately 319,000 km of roads in Quebec, including highways, national roads, collector roads, streets, bridges and overpasses, access roads and local roads (Ministère des Transports du Québec, 2015b; see Figure 3). There are also more than 300,000 kilometers of multi-use roads in forest settings.

Aging of infrastructure increases its vulnerability and maintenance costs. The average age of infrastructure provides a means of evaluating the condition of the network and the need for investments to ensure its maintenance. Reinvestment in this area since the early 2000's has reduced the average age of roads in Quebec from 18 years in 2000, to 13 years in 2009 (Gagné and Haarman, 2011).

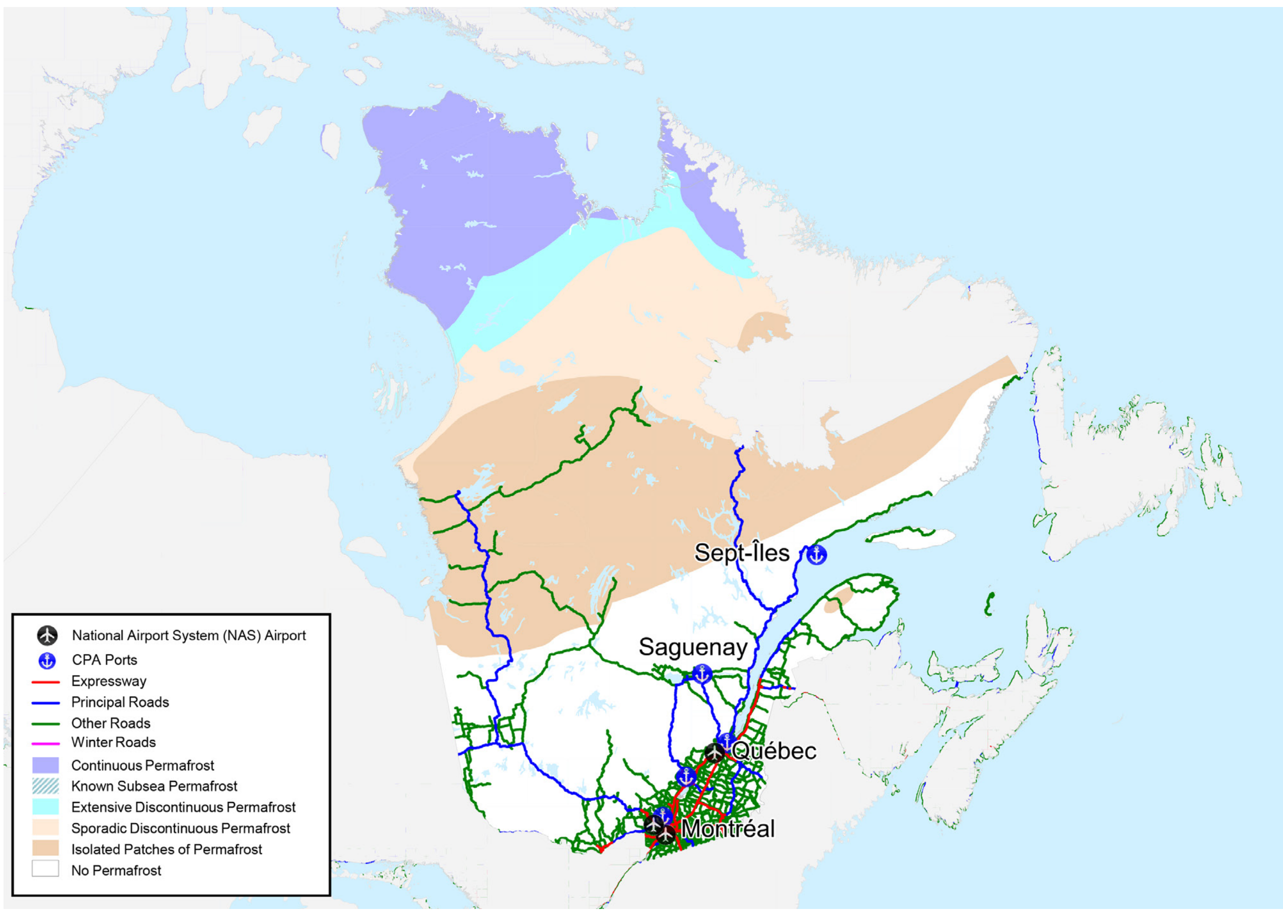
Certain regions are heavily dependent on a single road link for their regular supply and mobility needs. Accessibility to these regions could be significantly compromised after a major weather event (e.g., flood, landslide, erosion etc.,) causes damages to the road link.

Although user behaviour is often the cause of accidents, the contribution of weather conditions must also be considered in road safety management (Andrey, 2010). Moreover, the number of collisions increases during times of precipitation (Andrey and Mills, 2002). However, the number of road accidents has been on the decline since 2007, in Quebec and elsewhere in Canada.

Some tourist regions such as the Gaspé, the Magdalen Islands, the North Shore and the lower St. Lawrence have developed facilities and activities to promote the region and attract visitors. Theme routes,[7] such as the Route des baleines or the Route des Navigateurs, and national parks that draw on their relationship with the river (such as the Saguenay-St. Lawrence Marine Park and the Parc National du Bic) are pillars of tourist development in these regions. Loss of access to these parks due to erosion of roads bordering the river would affect economic and social development. The same is true for the Routes bleues, another theme route, and its related infrastructure, which are also affected by changes observed along the St. Lawrence (coastal erosion, decreasing water levels, etc.).

Finally, some portions of the Quebec road network are highly congested with traffic, especially in the two metropolitan areas of Québec City and Montréal (MTQ, 2013a). Reduced speed due to congestion increases transit time as well as the cost of road transportation. It also reduces the dependability or perceived dependability of the mode of transportation. Traffic congestion combined with the projected rise in summer temperatures and increased frequency, duration and intensity of heat waves, could also have important implications for road freight management systems in the future, particularly concerning new refrigeration requirements, choices of materials for pavement, and other factors. (Goodwin, 2004; James and James, 2010).

Figure 3: Map of road transportation in Quebec.



7 For more detailed information, visit http://www.sentiermaritime.ca/index.asp?id=522.

2.2 MARINE TRANSPORTATION

Marine transportation is closely tied to a number of key sectors of the Quebec economy, and plays a major role in the movement of goods along the St. Lawrence corridor. Marine transportation activity, including shipping, port and cruise tourism services, has been increasing in Quebec since 2000. In 2011, these activities represented sales of more than $2.3 billion.

Ports along the St. Lawrence primarily move mineral ore, forestry products, agricultural and food products, manufactured goods, fuel and chemical products, and machinery (St. Lawrence Economic Development Council, 2015), in addition to supplying industries and communities (see Figure 2).

Nunavik, the coastal communities in the Eeyou-Istchee James Bay region and several municipalities along the North Shore are also equipped with marine infrastructure consisting of breakwaters, access ramps, beacons, or floating pontoons that serve the local population. In most cases, this infrastructure is the main supply link for remote communities. Some larger marine infrastructure serves industrial activity in these same regions. For example, a private deep-water wharf at Baie Déception in Nunavik serves a mining operation, and other private industrial dock projects could be developed in the region with increased mining activity.

The main commercial ports in Quebec include the ports under the jurisdiction of Canadian port authorities in Montréal, Trois-Rivières, Québec City, Saguenay and Sept-Îles. Other ports and marine infrastructure play an important role in supporting recreational tourism activities and other local needs.

The port network in Quebec handled 130.4 million tonnes of goods in 2011, three quarters which were international goods (Statistics Canada, 2011). The Port of Montréal is the largest container port in eastern Canada (Port of Montreal, 2015), receiving more than one million 20-foot equivalent unit containers annually. Playing a pivotal role in the transportation of goods, it is directly connected to rail and road networks. Each week 80 trains pass through the port, with 5,000 trucks arriving and leaving each day (Port of Montreal, 2015). The ports of Sept-Îles-Pointe-Noire, Port-Cartier, Baie-Comeau and HavreSaintPierre on the North Shore are among the ten largest ports in Quebec in terms of tonnage of goods handled (Ministère de l'Énergie et des Ressources Naturelles, 2011). The deep water port in Québec City that specializes in transshipment serves as a true intermodal hub for trade in the Great Lakes – St. Lawrence River corridor. The port in Sept-Îles is the third largest port in Canada in terms of bulk tonnage handled.

Ferries managed by the Société des traversiers du Québec are linked to the land transportation system to enhance people's mobility. In some urban areas, connections to public transportation networks also facilitate intra-regional and inter-regional travel. Ferry activity, however, is subject to economic fluctuations (ROCHE-Deluc, 2010). Ferries are also exposed to weather conditions and the impact of climate change. On the St. Lawrence, 18 ferries operate year-round and serve more than five million passengers and more than two million vehicles (Société des traversiers du Québec, 2014).

2.3 RAIL TRANSPORTATION

The Quebec rail network mainly follows the St. Lawrence valley and extends to the north of the province toward regions of Abitibi-Témiscamingue, Saguenay-Lac-Saint-Jean and Chibougamau, the North Shore, and Labrador (see Figure 2). Among other services, it transports intermodal containers for forestry products, mining products and aluminum. A large number of rail cars run through the Montréal and Québec City regions on their way to other Canadian provinces and the United States (Ministère des Transports du Québec, 2008).

Several rail freight service companies serve Quebec. The largest are Canadian National (CN), Canadian Pacific (CP) and CSX Transportation, which together make up close to 58% of the current network in Quebec. A few manufacturing or resource extraction companies, such as Arcelor Mittal or Rio Tinto Alcan, also operate some of the province's railway lines. With a few exceptions, railways with tracks extending outside of Quebec are under federal jurisdiction, whereas all other tracks are under provincial jurisdiction. Transportation of people is primarily provided by Via Rail Canada Inc., but also by the Québec North Shore and Labrador Railway, by Amtrak for sections in the southernmost part of the province that lead to the United States, and by commuter trains and tourist trains.

Demand for rail services has increased somewhat since 2001, both for the transportation of goods and travelers (Réseau des chemins de fer du Québec, 2011). The rail network under provincial jurisdiction has grown in the last 20 years, from 564 kilometers of rail in 1993, to more than 1,700 km in 2015 (Ministère des Transports du Québec, 2015a).

2.4 AIR TRANSPORTATION

The airline sector provides transportation for passengers, freight and other activities, such as aeromedical evacuations, ice patrols, aerial application of products and more. Regarding freight services, close to 146,000 tonnes, equivalent to $3.7 billion, were transported by the 380 air transportation companies in Quebec in 2010 (MTQ 2013a).

There are two international airports (Montréal and Québec City) and various regional airports, 26 of which are owned by the Ministère des Transports (see Figure 2). There are also close to 150 aerodromes, approximately 50 seaplane bases and approximately 50 heliports.

Passenger air traffic in Quebec increased by 4% between 2013 and 2014, reaching 16.5 million passengers. (Statistics Canada, 2014). Passenger air traffic should continue to increase, according to 2012-2022 forecasts.

3.0 A CHANGING CLIMATE[8]

Climate risks for the transportation sector (infrastructure and services) vary by location and season. These considerations are important to better understand the potential impacts of expected changes, as they could accentuate the sector's vulnerabilities.

Québec's large territory and varied topography (altitude of up to 1,652 m) help to create different climates (Ouranos, 2015). These range from a cold and humid continental climate in the southern and eastern parts of the province to a sub-polar continental climate in the central regions, a polar tundra climate up north and more of a maritime climate in the coastal areas towards the Gulf of the Saint-Lawrence. All of Québec is affected by climate change and certain trends are already being observed.

3.1 RISING TEMPERATURES

Since 1950, temperature trends for both average and extreme temperatures have shown an increase in practically all regions in Québec, with extreme cold temperatures showing the most significant change. Over the period 1951-2010, decreases were recorded in the number of cold days and cold nights as well as in the length of cold spells (Donat et al., 2013). A significant increase was also observed during this same period in the number of hot days, hot nights and length of heat spells.

Projections suggest that these trends will continue, with northern latitudes being even more affected. Moreover, warming trends will be more prominent for extreme minimum and maximum temperatures

[8] This chapter presents the current and future climate conditions for Québec for the indicators most relevant to the transportation sector. Unless otherwise indicated, all information is from the reference document "Towards Adaptation" (Ouranos, 2015), a state of knowledge document published by Ouranos in 2015. More information can be found in Chapter 1 of this document.

than for average temperatures. Figure 4 shows average observed and projected summer and winter temperatures for all of Québec.

Figure 4a: Average observed and projected summer temperatures for all of Quebec. (Source: Ouranos)

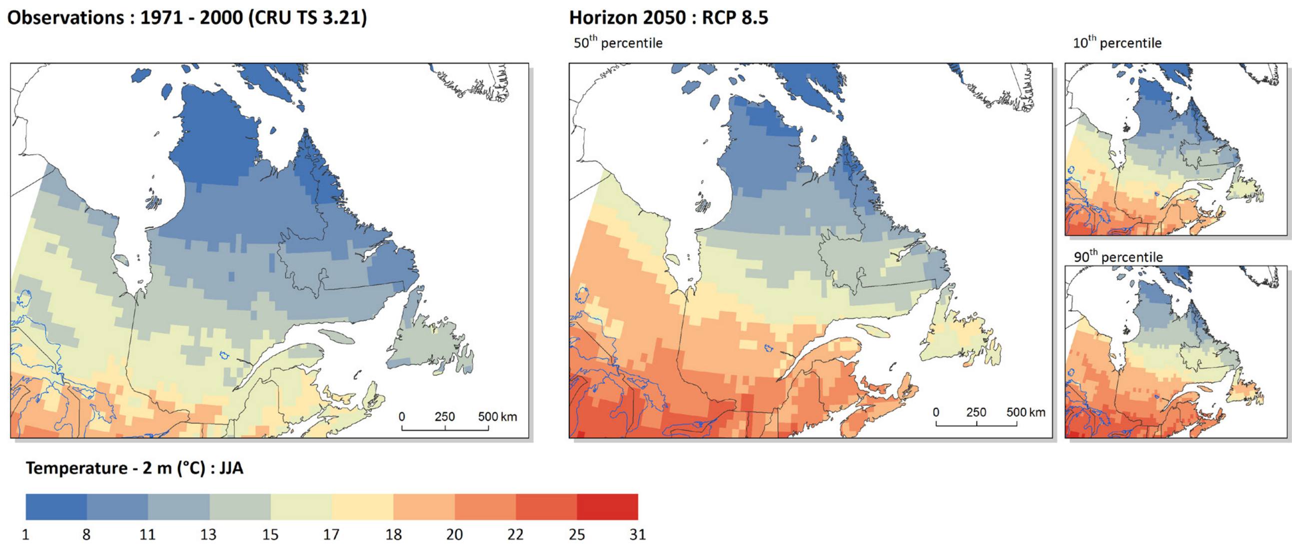


Figure 4b: Average observed and projected winter temperatures for all of Quebec. (Source: Ouranos)

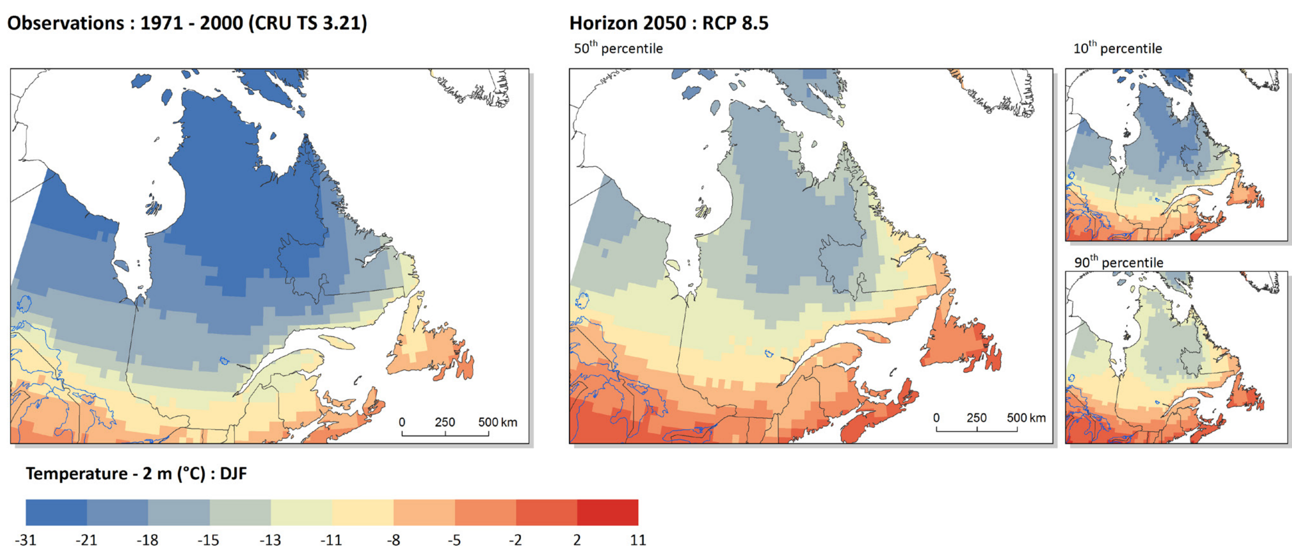
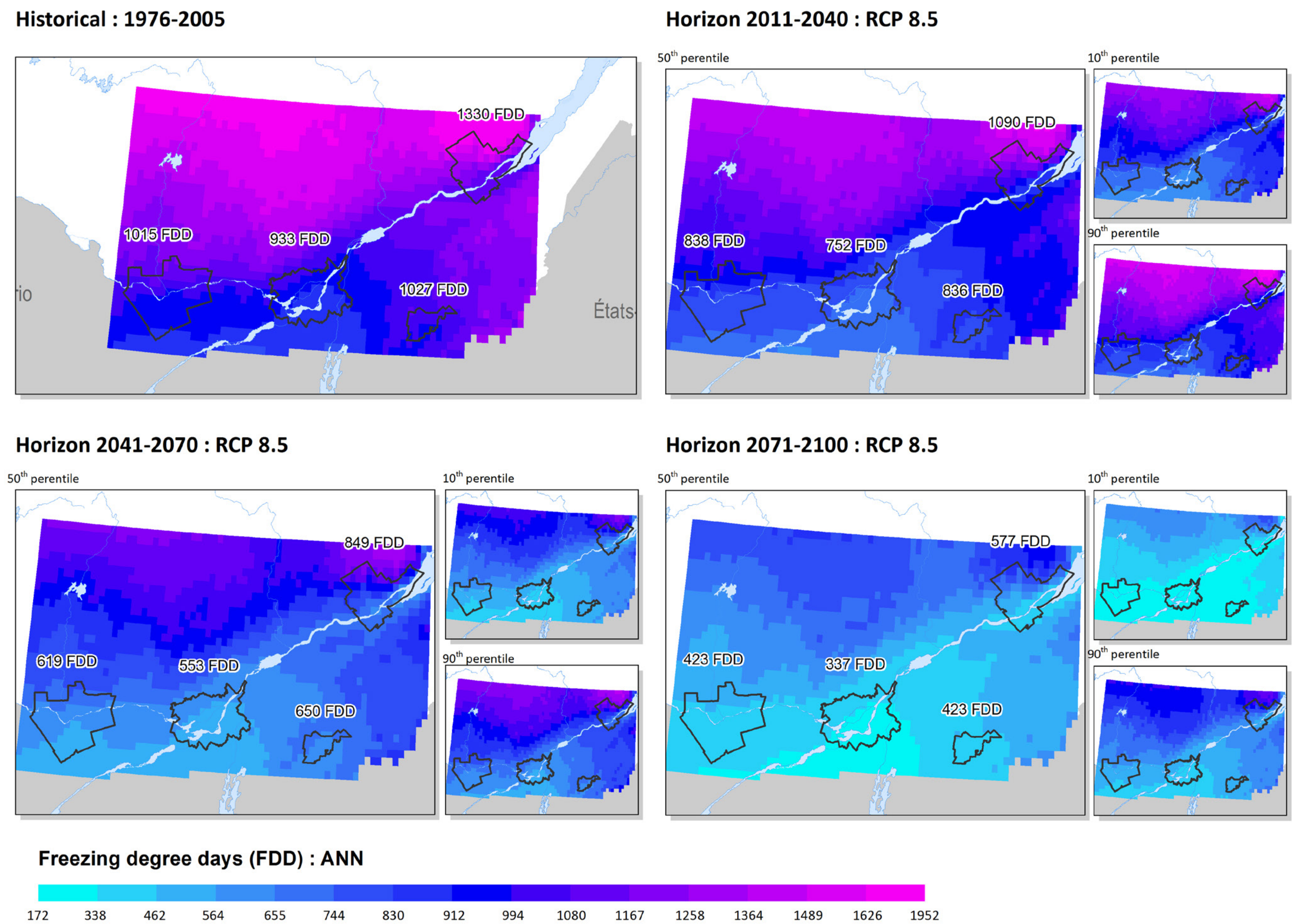


Figure 4: Observed average summer (JJA: June, July and August) (Figure 4a) and winter (DJF: December, January and February) (Figure 4b) temperatures for the 1971-2000 period (left panel) and projected (right panels) for the 2050 horizon (2041-2070). The observed average is calculated from CRU TS 3.21 dataset (CRU TS = Climatic Research Unit Timeseries, 3.21 dataset is the name of the release). Future maps present the ensemble median (i.e., the median of all the available projections) as well as the 10th and 90th percentiles (i.e., lower and higher bounds) of 29 future climate scenarios. Future climate scenarios were produced using the "delta" method calculated from the CMIP5 (Coupled Model Intercomparison Project Phase 5) simulations (RCP 8.5) and applied the observed data (see Charron, 2014). (Source: Ouranos)

Warming temperatures will also bring changes to other indicators that affect the transportation sector. For example, the cold season will begin later and end earlier, resulting in a season close to one month shorter in the south of the province by 2050 (Logan et al., 2016, in press). Projections of degree-days of freezing are shown in Figure 5.

Figure 5: Simulated historical and future conditions of annual freezing degree days calculated from an ensemble of climate scenarios (n=11) following RCP 8.5 greenhouse gas forcing trajectory. The historical panel represents the median of the 11 climate scenarios[9] while future horizons panels represent the median (i.e., the median of all available projections) (left), as well as the 10th and 90th percentiles (i.e., lower and higher bounds) (top and bottom right) of the climate scenario ensemble. The 30 year regional mean of four large urban centres (Gatineau/Ottawa, Greater Montréal, Sherbrooke and the Québec city region) is indicated above the black regional contours. (Source: Ouranos)



Recent observations show a rise in the number of daily freeze-thaw cycles during warmer years (Chaumont and Brown, 2010). However, projections for mid-century suggest a decrease in the number of freeze-thaw cycles. Indeed, from 2050, it is likely that the cold season will shorten to the extent that it will be difficult to reach the same number of freeze-thaw cycles currently observed in a given season.

9 Note that in this case the historical climate normal values are not calculated from observed data, but instead from simulated climate model output which has been corrected to consider observed values using a post-processing method.

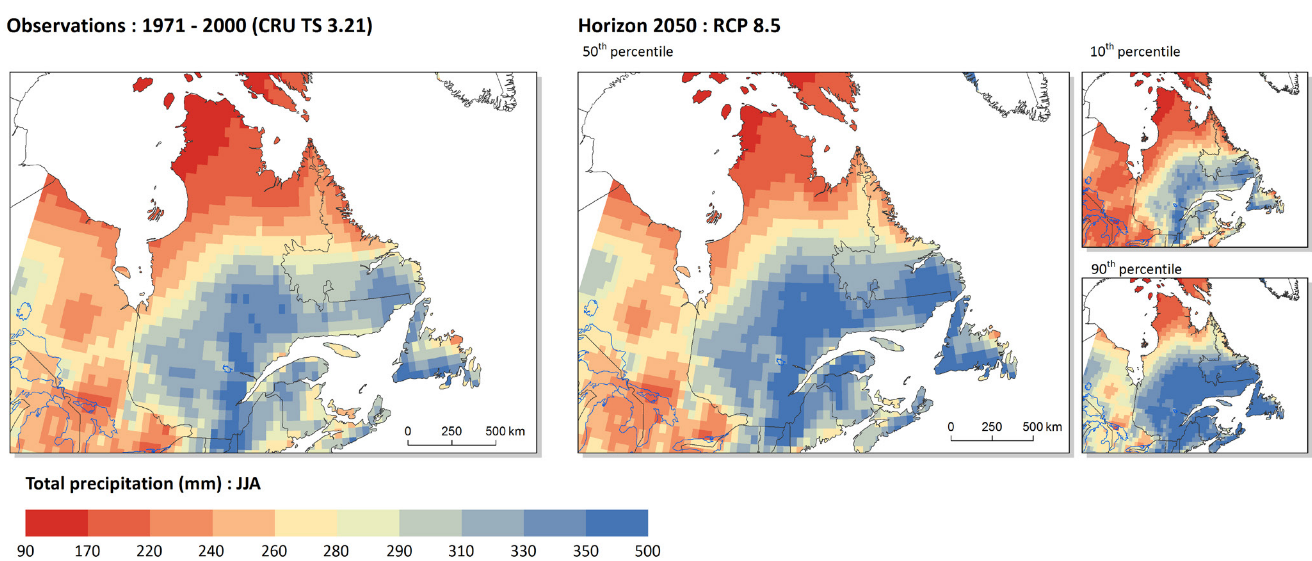
3.2 MORE INTENSE PRECIPITATION EVENTS

Total annual precipitation from observed data shows significant upward trends for many of the weather stations located in the south of the province. For some of these stations, the trends are associated with increases in spring and fall precipitation.

Increases in precipitation are expected in winter and spring throughout Québec. In the northern and more central regions, this would also be the case in the summer and fall seasons. As in the case of temperatures, these increases will be more significant for extreme precipitation events than for averages. In fact, all climate models agree on future upward trends for extreme precipitation events, everywhere in Québec, although these changes are more substantial moving northward. This applies for maximum annual amounts in addition to all durations and frequencies. For example, a maximum annual rainfall event with a 20-year return period over the 1986-2005 timeframe could occur more frequently by 2046-2065 with a return period of around 7 to 10 years. Preliminary studies suggest that future climate conditions could be more conducive to thunderstorms, which are usually accompanied by larger quantities of precipitation, although the robustness of these projections is uncertain.
For winter precipitation, the proportion of snow and rainfall relative to total accumulation depends on temperature. Given that the climate has been warming in the recent past, downward snow precipitation trends are already being observed in the south of Québec. An analysis of several different data sources reveals that snow cover duration has decreased by approximately 2 days per decade in the south of Québec between 1948 and 2005.

Even if snowfall events decrease due to a shorter cold season, rainfall events during this season should increase with warming temperatures in winter (see Figure 6). Changes in snow cover with respect to these trends will vary according to the region, altitude, climatic regime, type of surface and vegetation. Compared to the 1970-1999 average, snow cover duration by 2041-2070 could decrease by up to 25 days in the North of Québec, from 25 to 45 days in the central region, from 45 to 75 days for the Gulf of the St. Lawrence and between 45 and 65 days for the south of Québec.

Figure 6: Observed total summer (JJA: June, July and August) and winter (DJF: December, January and February) precipitation for the period 1971-2000 (left panel) and projected (right panels) for the 2050 horizon (2041-2070). The observed average is calculated using the CRU TS 3.21 dataset (CRU TS = Climatic Research Unit Timeseries, 3.21 dataset is the name of the release). Future maps present the ensemble median (i.e. the median of all available projections) as well as the 10th and 90th percentiles (i.e., lower and higher bounds) of 19 future climate scenarios. Future climate scenarios were produced using the "delta" method calculated from the using CMIP5 (Coupled Model Intercomparison Project Phase 5) simulations (RCP 8.5) applied to the observed data (see Charron, 2014). (Source: Ouranos)



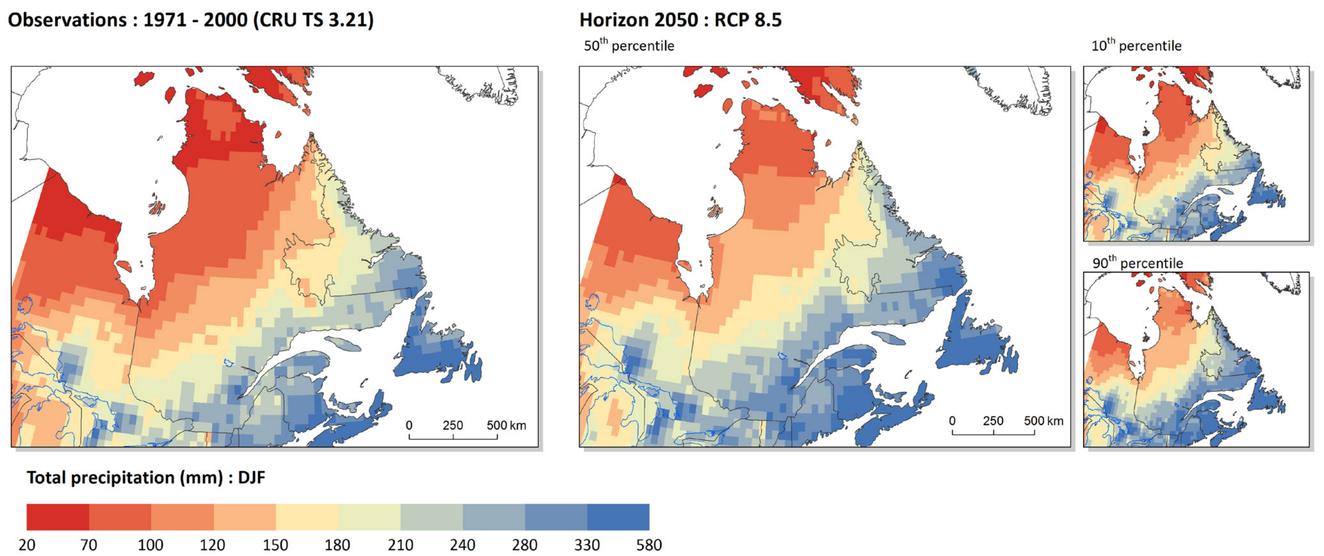
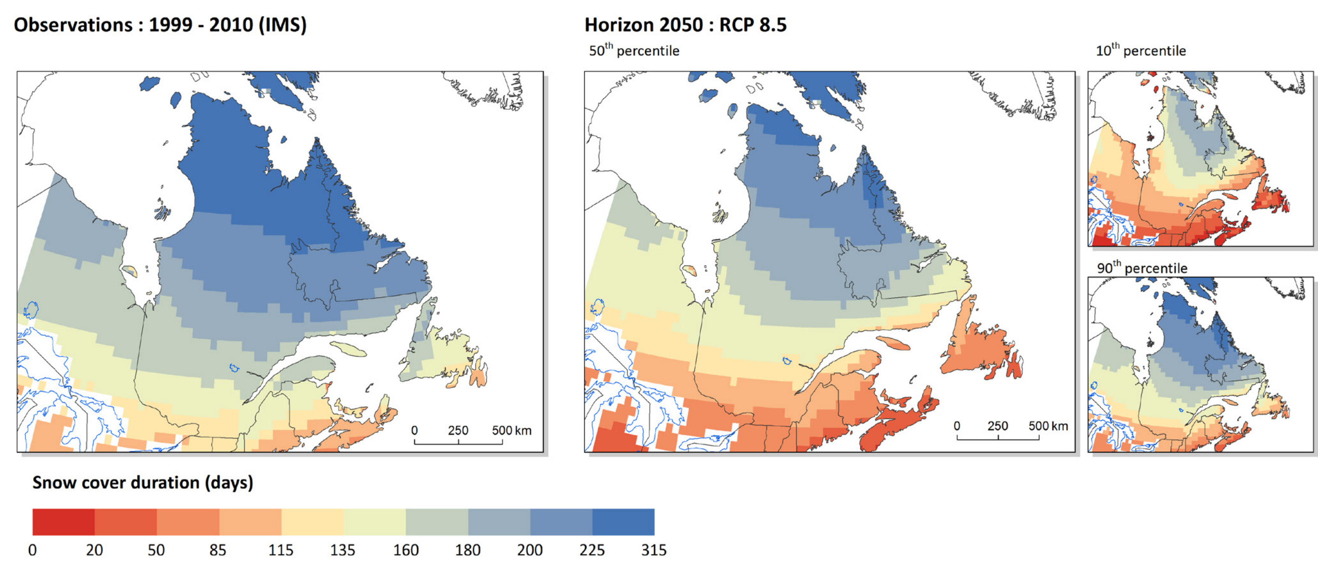


Figure 7: Observed snow cover duration for the period 1999-2010 (left panel) and projected (right panels) for horizon 2050 (2041-2070). The observed average is calculated using the IMS 24 dataset (IMS Ice mapping System 24 km resolution) (National Ice Center, 2008). Future maps present the ensemble median (i.e., the median of all available projections) as well as the 10th and 90th percentiles (i.e., lower and higher bounds) of 19 future climate scenarios. Future climate scenarios were produced using the "delta" method calculated from the CMIP5 (Coupled Model Intercomparison Project Phase) (RCP 8.5) and applied to the observed data (see Charron, 2014). (Source: Ouranos)



With respect to freezing rain, this is a phenomenon that predominantly affects the Saint-Lawrence valley due to its morphology and position (Ressler et al., 2012). While great progress has been made to improve knowledge in terms of the conditions likely to generate this type of event, it remains uncertain whether the number, duration and intensity of these events will change in Québec over the coming decades.

3.3 UNCERTAINTY CONCERNING WINDS

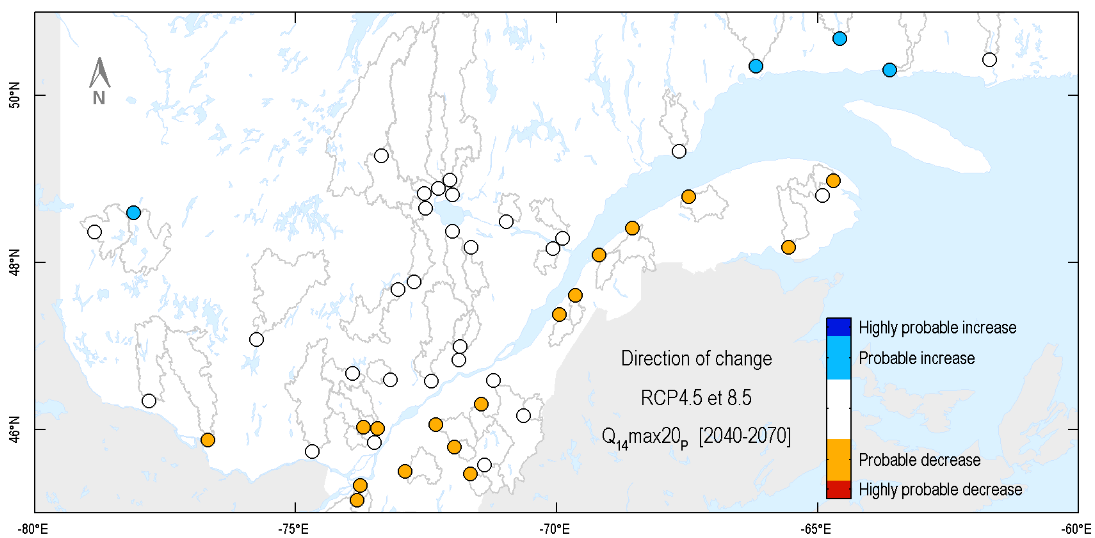
Average observed wind speeds for the great majority of weather stations varies only slightly from one season to another. With the exception of a few stations that show minor increases, most stations in Québec show downward trends in average wind speed throughout the year over the 1953 to 2006 period.

Projections of future winds remain uncertain since very few studies exist on this subject. Additional analyses based on a greater number of climate simulations at finer resolutions would be required.

3.4 FLUCTUATING AVERAGE RIVER FLOWS

Average river flows are expected to increase in winter throughout Québec by 2041-2070. Conversely, for the same time period in the south of Québec, decreases in average flows are likely to occur in the summer, spring and fall seasons although consensus between model outputs is not as high. Figure 8 shows expected changes in spring freshet, the spring thaw resulting from snow and ice melt in rivers. More information on future changes to watersheds in southern Québec can be found in the "*Atlas hydroclimatique du Québec méridional*" (Centre d'expertise hydrique du Québec, 2015).

Figure 8: The hydrological indicator $Q_{14}max20_p$ provides an indication of the volume of spring freshet for the 20-year return period. (Source: Centre d'expertise hydrique du Québec)



3.5 RELATIVE SEA LEVEL

Changes to relative sea level vary at regional scales because of several factors including marine currents, atmospheric circulation, seawater density (itself affected by surface temperatures, freshwater supply through waterways or glacier melt), the proximity to ice sheets and glaciers (gravitational effects) and other geophysical phenomena (rotational effects). Some of these phenomena occur in combination and cancel each other out or fluctuate in time over inter-annual or decadal scales, making it difficult to detect significant trends. As a result, rising relative sea levels will affect the marine estuary and Gulf of the St. Lawrence. In the Hudson Bay, a drop in relative sea level is expected due to postglacial isostatic adjustment in this area diminishing the effect of sea level rise. More information on this can be found in Chapters 3 and 8.

3.6 A PROGRESSIVE LOSS OF SEA ICE COVER

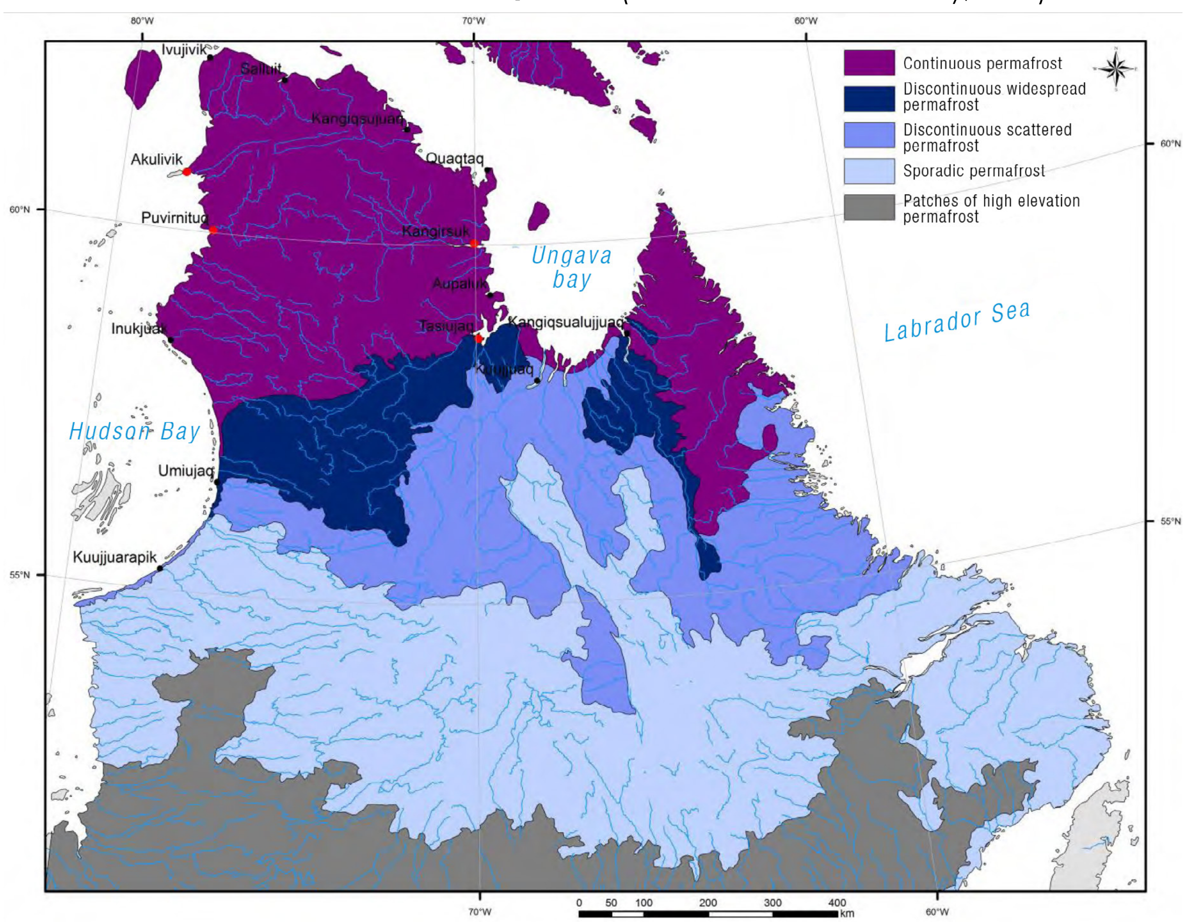
Warming temperatures will also affect sea ice cover (see Chapter 3). More specifically for Québec, a study of the marine estuary and Gulf of the St. Lawrence shows ice cover reductions between 1998 and 2012. The freeze-up season is shorter than in the past despite the fact that interannual variability is quite high (Senneville et al., 2014). This same study showed that the proportion of maximum ice cover in the region diminished from approximately 47 % (1968-1998) to 36 % (1998-2013).

These trends are likely to continue and projections indicate that freeze-up could arrive about 10-20 days later while thawing could begin 20 to 30 days earlier by 2041-2070, compared to 1982-2011 in the Gulf of the St. Lawrence. In the Hudson Bay area, the ice-free season could extend up to two months longer towards mid-century. Other regions in Québec could also be affected however, existing studies on the subject do not make it possible to determine the magnitude of expected changes.

3.7 THAWING PERMAFROST

Québec's northern region is located in an area of permafrost as illustrated in Figure 9. Permafrost is very sensitive to warming temperatures and changing precipitation patterns (see Chapter 3).

Figure 9: Permafrost distribution in northern Québec. (Source: Allard and Lemay, 2012)



These conditions will affect the transportation sector at different levels. The following section will describe in more detail the main vulnerabilities for the different modes of transportation throughout Québec.

4.0 TRANSPORTATION VULNERABILITIES TO CLIMATE CHANGE

Although the projected climate outlook shows that all regions of Quebec can expect rising temperatures and heavier precipitation events, the consequences will affect each economic activity differently, including transportation infrastructure and mobility. Extreme weather events are likely one of the greatest risks for all regions of Quebec. In addition, the built environment in Quebec is aging, and certain transportation infrastructure is reaching the end of its useful life or needs considerable refurbishment (Canadian Infrastructure Report Card, 2012). It may therefore be more vulnerable to the impacts of climate change.

The following sections present the main climate vulnerabilities identified for road, marine, rail and air transportation in Quebec. One section also deals with the telecommunication networks on which these modes of transportation depend. The vulnerabilities described are those of infrastructure, but also, more generally, those of transportation services operations and management. More information is available on road transportation, which underscores the importance of this mode in terms of modal share, as well as current research and development efforts.

4.1 GROUND TRANSPORTATION

4.1.1 VULNERABILITIES OF ROAD TRANSPORTATION IN SOUTHERN QUEBEC AND ALONG THE ST. LAWRENCE

In the area that extends to the east of Québec City to the lower North Shore (covering the Lower St. Lawrence, the Gaspé Peninsula and the Magdalen Islands), roads and villages are located along the coast. One third of the population in this region and close to 60% of national roads are located less than 500 metres from the shoreline (Drejza et al., 2014; Boyer-Villemaire et al., 2014). Some portions of Route 132 that follow the entire south shore of the St. Lawrence, from the United States border west of Montréal to Gaspé, are located anywhere from a few meters to a few dozen meters from the shore (McHugh et al., 2006).

In the 20th century, this proximity to the river was seen as favourable for transportation, due to the supply of natural resources and marine exploitation. However, the establishment of roads and facilities along the St. Lawrence now appears to be a factor that exacerbates their vulnerability (Drejza et al., 2015). The rise in annual average temperatures and especially rising winter temperatures recorded since the 1980's (Bernatchez et al., 2008, Bernatchez, 2015; Savard et al., 2008) have various consequences such as a reduction in ice cover, a relative rise in sea level and an acceleration of cryogenic processes, which contribute to erosion (Bernatchez et al., 2011; Bernatchez et al., 2015; Boyer-Villemaire et al., 2014). More than half of the St. Lawrence estuary and gulf coastlines are prone to erosion (Drejza et al., 2015). Along the estuary and gulf coastal zone, 294 kilometers of roads are considered to be at risk by 2065 (Bernatchez et al., 2015). The growth in the built environment along the St. Lawrence estuary increases the magnitude of the impact (Bernatchez and Fraser, 2011; Bernatchez et al., 2015; Ouranos, 2015). The impacts of climate change are already being felt on road infrastructure (Drejza et al., 2014). Several studies have found that erosion problems have required considerable investment to move roads or build remedial works (Ouranos, 2015; Bernatchez et al., 2015).

Freeze-thaw cycles are also causing the erosion of several rock cliffs in the St. Lawrence estuary and gulf, in southern Quebec (Bernatchez et al., 2014) (*see box on coastal erosion in the Magdalen Islands*), especially in the middle of the cold season by contributing to the continuous expansion of water in the ground, in cliffs or in road surfaces, which can cause cracks, splitting and detachment of cliffs or mud slides (Boucher-Brossard and Bernatchez, 2013; Drejza et al., 2015). Although surfaces are usually designed to resist frost for approximately four months and to withstand large quantities of snow and melt, rapid snow and ice melt renders these surfaces more vulnerable. Mild temperature periods, which are projected to rise in frequency (Ouranos, 2015) also increase and intensify roadway damage (Chaumont and Brown, 2010; Doré et al., 2014). Roadways currently have a reduced useful lifespan specifically because of the cracking phenomenon that lets rain water penetrate and consequently increase the saturation level of the soil and of roadway materials (Masseck, 2014).

The relative rise in sea level of approximately 40 centimeters since the beginning of the 20th century exposes several portions[10] of the Quebec road system, in particular along Highway 20 and Route 132 (Bernatchez and Fraser, 2011). The rise of relative sea level, among other things, reduces soil stability under buildings, infrastructure and roads in Quebec (Bernatchez et al., 2012). It decreases the stability of the transport system as a whole and, consequently, that of the supply and mobility system. The acceleration of this phenomenon is likely to increase the risk of road flooding from storm surges in the St. Lawrence corridor (Savard et al, 2016. Lemmen et al., 2008; Intergovernmental Panel on Climate Change, 2013). The problem of waves and tides on the Quebec coast along the Gulf and up the middle estuary is further compounded by the fact that the coast will be less protected by decreasing ice cover. In addition, submersion events could become increasingly frequent and intense and reach areas that, until now, were not highly affected. Without adaptation measures that respect the coast’s geomorphology, erosion will continue to affect the natural system, the integrity of the built environment and the quality of life for most communities living in coastal areas (Bernatchez, 2015; Ouranos, 2015).

Riprap[11], seawalls, jetties, etc., are forms of protection that reinforce the public’s sense of safety (Cooper and Pile, 2014; Friesinger and Bernatchez, 2010; Linham and Nicholls, 2010). That said, these methods are costly and may be a factor in the breakdown of some natural slopes and beaches (lowering, shrinking, etc.), especially if they are used to protect slopes in loose zones (Bernatchez et coll., 2008; Bernatchez, 2015). Where sediment is loose, riprap reduces beaches’ natural ability to absorb the energy from storm surges. It is therefore likely to contribute to erosion (Drejza et al., 2014; Bernatchez et al., 2011; Bernatchez and Fraser, 2011) and scour at the edges of riprap and other artificial linear structures. Furthermore, turbulence that occurs when water hits the edges of a structure erodes the sand of any unprotected neighboring areas (Bernatchez and Fraser, 2011).

In the SeptÎles and Percé regions, the width of beaches has shrunk by 85% and 44% respectively, where the shoreline was artificially enhanced by a rigid protective structure (Bernatchez and Fraser, 2011). Other effects of climate change on terrestrial infrastructure are associated with the increased intensity of rain precipitation in the winter that could create negative impacts, in particular for the management of surface water runoff (Groleau et al., 2007). For example, existing drainage systems on coastal roads can sometimes contribute to the formation of ravines where water collects (Ministère de la Sécurité publique du Québec, 2012), and this may trigger landslides and speed up erosion. On the other hand, in the south of the province, around the St. Lawrence Valley, rising average temperatures and changes in precipitation patterns could have a positive impact due to less snow and ice on roads, which could translate into lower costs for ice and snow removal of roads (Webster *et al*., 2008).

Other effects of climate change on land infrastructure are summarized in Table 2.

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10 A portion of road corresponds to a route itinerary. It can be regional or local.

11 Riprap is an adaptation option built by dumping of stones of various size with a soft slope in order to absorb and dissipate wave energy before it reaches the shore (Circé et al., 2016)

Table 2: Summary of certain climate change effects on roadways. Adapted from Thiam (2014)

Causes	Possible effects on roadways
Rise in temperature in cold areas and increase in the number of mild periods in the winter	Decrease in the freezing index in winter, decrease in frost depth resulting in less roadway deterioration due to frost heaves and reduction in thermal cracking
	Possible increase in damages due to partial thaw of subbase (rutting and cracking and weakening of roadways)
Increase in extremely hot temperatures	Increase in flow ruts (creep effect)
Increase in the availability of water during the summer	Rise in the level of the water table, causing a weakening of the structural layers and a decrease in lifespan Increased rutting (Korkiala-Tantuu and Dawson, 2007).
Increase in the frequency and intensity of extreme rainfalls	Increase in water content of roadway soil immediately after rain
	Increase in water content of roadways and decrease in their rigidity

4.1.2 LAND TRANSPORTATION VULNERABILITIES IN NUNAVIK

Transportation infrastructure in northern villages is built on continuous, discontinuous or sporadic permafrost (see Figure 10 in Chapter 3). Permafrost thaw, especially due to rising temperatures, and also by snow and drainage management, decreases the structural integrity of roads (Doré et al., 2014; Ouranos, 2015). The differential settlement associated with permafrost thaw, and its structural consequences on embankments specifically, affect drainage networks and alter their integrity (Beaulac, 2006; Dumais and Doré, 2013) by causing cracks or settling that require more frequent maintenance, as is the case for access roads to the Umiujaq (Figure 10) and Salluit airports.

Figure 10: Significant settling on the Umiujaq access road. (Source : Allard, M., Fortier, R., Sarrazin, D. et al., 2007)

A changing climate also affects the mobility of local populations in Nunavik. In winter, frozen lakes and streams offer various possibilities for travel by all-terrain vehicle, snowmobile and dog sled. As the frost period shortens, these possibilities are reduced (Tremblay et al., 2006; Nickels et al., 2005; Bernier et al., 2014). Changes in ice conditions and the shortening of the period when ice is present complicate access to natural resources and to subsistence activities (Clerc et al., 2011; Tremblay et al., 2006). Access to hunting, gathering, and fishing territory is essential to northern communities, and their local economy. Alternative trails can be used, but this change in traditional land reduces possibilities to exploit quality nutritional resources (Barrett, 2013). Moreover, local know-how and experience no longer allow snow and ice conditions to be predicted as reliably to plan and organize travel (Nickels *et al*., 2005; Samson *et al*., 2013). These consequences are likely to affect the cultural identity and health of northern populations, in addition to their economic development.

4.1.3 EXTREME WEATHER EVENTS AND ROAD TRANSPORT

Extreme weather events will affect road transportation in all regions. Events such as heavy precipitation, storms and temperature variations (e.g., freeze-thaw cycles) cause accelerated wear of road infrastructure (Auld and MacIver, 2005; Case, 2008; Larrivée, 2010). Moreover, when infrastructure nears the end of its useful life it becomes more vulnerable to extreme weather events (Ouranos, 2015). This could increase road maintenance requirements. The integrity and performance of culverts and bridges may also be affected.

In Nunavik, an increase in the occurrence of extreme weather events will have an impact on transportation. Some events (e.g., blizzards, wind, heavy snow) reduce visibility, affecting driving conditions and the safety of travel on land, causing delays and isolating communities from essential services.

Extreme weather events can also isolate communities, particularly those that depend on a single mode of transportation. The absence of alternative transportation services contributes to the vulnerability of populations in these regions. For example, the strong waves and storm surges produced by strong winds that hit the shores of the Lower Saint-Lawrence, Gaspé, Magdalen Islands and the North Shore on December 5th and 6th, 2010 generated tides 5.54 meters above chart datum in Rimouski, an exceptional height (Quintin et al., 2013). The storm flooded several roads, including Routes 132, 199, 299, 198, rendering them impassable to traffic. The assault of the waves and strong rains damaged roadways, certain retaining walls, and the area surrounding walls and culverts (see Figure 11). On the basis of replacement costs per kilometer and taking into account the existing geographical situation and means of coastal protection (Bernatchez et al., 2015), damage was estimated at several million dollars and several hundred people had to be evacuated (St-Amour, 2011). This winter storm demonstrates the effects that a combination of factors, such as a reduction in ice cover, a relative rise in sea level, and wind direction and storms, can have on natural and built environments.

Figure 11: Major deterioration of the Route 132 roadway in the Gaspé Peninsula, in December, 2010.
(Source: Ministère des Transports, de la Mobilité durable et de l'Électrification des transports du Québec)

Storm surges are related to the height of the sea above the astronomical tide during heavy storms. More frequent storm surges could increase marine submersion events as well as erosion of natural environments such as beaches and dune ridges. Storms can also cause the collapse of breakwaters, dams and other hydraulic structures (Bernatchez et al., 2012).

If sandy beaches are exposed to strong winds for long periods of time in the spring and fall, the winds can carry sand and contribute to moving dunes. This affects road maintenance in the Magdalen Islands.

The main meteorological factors that can affect forest fires include temperature, wind speed and direction, relative humidity, precipitation and atmospheric stability (Ordre des ingénieurs forestiers du Québec, 2009). These factors vary in time and space, and will likely have a greater adverse effect in the northwest region of the province (Boulanger et al., 2013). The section of the road system located within the limits of commercial forestry operations primarily serves this industry. Fires caused by lightning can have a major impact on road access to resources and at the same time, on the vitality of these industries' operations and the communities that depend on them.

In 2013, the Société de protection des forêts contre le feu (SOPFEU) fought 84 fires (SOPFEU, 2014). During the summer of that same year, major fires at the northern limit of the commercial forestry operations required protection of the Eastmain and Baie-Johan-Beetz communities. In the James Bay region, the only road connecting Matagami to Radisson was closed for over 300 kilometers, requiring the evacuation of several hundred workers, leaving communities isolated by the flames (Gouvernement du Québec, 2013; see Figure 12).

Other types of disturbances to road transportation are also associated with extreme weather events. The uprooting of trees can disrupt road access due to the presence of debris. Also, transport planning and road maintenance could be disrupted due to the increased frequency and intensity of heat waves, as extreme heat can expose workers to occupational illnesses and injuries (e.g., heat stroke, heat exhaustion and heat cramps) (National Institute for Occupational Safety and Health, 2016). Recommended controls for reducing workplace heat stress include engineering controls (e.g., use of reflective or heat-absorbing shielding or barriers) and work practices (training, hydration, acclimatization and rest breaks) (National Institute for Occupational Safety and Health, 2016; Commission des normes, de l'équité, de la santé et de la sécurité du travail, 2016).

Figure 12: Forest fire in Chibougamau in 2005.
(Source: Société de protection des forêts contre le feu)

4.2 MARINE TRANSPORTATION

Some marine infrastructure dates back several decades, with the exception of northern infrastructure which was created at the turn of the 21st century by the provincial and federal governments and local authorities (Clerc et al., 2011; Ministère des Transports du Québec, 2011). Aging infrastructure, along with rising temperatures, reduced ice cover and increased frequency and intensity of extreme weather events, could increase marine transportation vulnerability.

4.2.1 MARINE TRANSPORTATION IN THE ST. LAWRENCE CORRIDOR

Scientific studies differ on the precise effect of climate change on fluctuations in water levels and flow between Lake Ontario and the St. Lawrence. Due to human interventions (e.g., buildings, water level control, etc.), it is difficult to establish the expected magnitude of associated levels and flow (Bouchard and Cantin, 2015). That said, simulations of the effect of higher temperatures on evaporation in the Great Lakes tend toward a possible reduction of levels and flow in the river portion of the St. Lawrence (Bouchard and Cantin, 2015). Conversely, in the lower St. Lawrence, in the estuary and the gulf, a changing climate would likely result in a rise in water level.

In the Montréal area, where an average of approximately 2,200 vessels pass each year and where more than one million twenty foot equivalent unit (TEU) containers are transported annually (Port of Montréal, 2015), this reduction could be in the order of 0.5 to 1.0 meter (Croley, 2003; Fagherazzi et al., 2004; Lefaivre, 2005; Roy and Boyer, 2011). Such a decrease could potentially cause a decline in the number of container ships stopping at the Port of Montréal (Slack and Comtois, 2016).

Anticipated changes to flow and water levels will affect marine traffic, as well as the entire intermodal freight transportation system organized around the Port of Montréal. At the same time, rising temperatures could provide a business opportunity to the Port of Montréal, due to a longer commercial navigation season upstream. The navigation season currently extends from the end of March to the end of December.

Tidal and ice movements associated with a rise in temperatures also affect sediment transport and silting. This could require adjustments in the management and maintenance of waterways and marine infrastructure. Sediment transport will likely affect navigation throughout the St. Lawrence corridor. In some strategic areas, the accumulation of sediment can reduce water levels and become an obstacle to navigation, which could increase the need to dredge channels and other areas surrounding marine infrastructure (Slack and Comtois, 2016).

Climate projections indicate that in 2040-2070 (compared to the 1982-2011 baseline period), freezing will occur 10 to 20 days later in the estuary and the Gulf, and thaw will be 20 to 30 days earlier (Senneville *et al*., 2014). As a result, the period of time when ice traditionally covers the St. Lawrence (the months of January, February and March) could be considerably shortened. Ice protects the coasts against wave and storm erosion. Although a reduction in the freeze-up period benefits navigation, an absence or decrease in ice cover will cause waves and storms to erode the coastline, even in the winter (Bernatchez *et al*., 2015; Bernatchez *et al*., 2010; Savard *et al*., 2010). Also, ice pile-up near marine infrastructure, caused by strong winds and sea currents, could contribute to the deterioration of these facilities.

The movement of ferries is also restricted by ice formation. When ice forms rapidly, icebreaking services may be needed from the Canadian Coast Guard, or services to some communities must be provided by air transport (Société des traversiers du Québec, 2014). See Chapter 6, case study 4: "Water levels, ice removal and adaptive management at the St. Lawrence Seaway Management Corporation".

4.2.2 MARINE TRANSPORTATION IN NUNAVIK

Climate change will affect storm systems and ice cover in Hudson Bay and, consequently, wave systems, extreme water levels and the moisture balance of coastal drainage basins (Clerc et al; 2012; Savard et al., 2016). The main cause of damage to marine infrastructure is the occurrence of strong waves associated with the passing of storms. Damage often occurs during extreme conditions, which are rare but very intense, and result in the combination of several phenomena (e.g. strong waves and extreme water levels) caused by the overlapping of spring tides and storm surges (Ouranos, 2015). Studies are underway to precisely quantify the vulnerability of Nunavik marine infrastructure to climate change.

4.3 RAIL TRANSPORTATION

In general, climate change vulnerabilities for rail transportation in Quebec are poorly documented. The rail management system, which involves private stakeholders and representatives from different levels of government (local, provincial and federal) interacting within an international institutional framework (Canada and the United States), contributes to the complexity of identifying vulnerabilities specific to Quebec infrastructure. Nevertheless, it is clear that any impact on the rail system has significant repercussions on the entire supply chain in Canada (QGI Consulting, 2009). See Chapter 5 for more information on these challenges.

Managing water runoff along train tracks is a major concern (AREMA, 2003). Extreme weather events and episodes of heavy rain can cause drainage and erosion problems, and increase the risk of a system breach due to disruptions in communications. For example, an episode of heavy rain in 2010 eroded the soil under the tracks of a section of the Arcelor Mittal railway. In addition to preventing the trains from moving, the erosion caused a rupture in the fiber optic cables that ensure communication throughout the system. Extreme weather events can also increase the risk of tracks being blocked by debris. As the climate continues to warm, extreme weather events and episodes of heavy rain will become more frequent and/or more pronounced (Ouranos, 2015) increasing the vulnerability of rail transportation in Quebec.

Brakes are also frequently tested during bad weather. In some sectors, particularly in the center of the province, personnel must remain on site and in personnel camps, during heavy storms. Maintenance work is then suspended and delays associated with performing inspections and additional maintenance costs are to be expected based on the increasing frequency of such events (Gouvernement du Québec, 2015).

Climate factors that contribute to triggering landslides (e.g., abundant rain, rapid snow melt and such other events likely to increase as the climate warms) have a tendency to increase rail system vulnerability. This would be especially significant in areas prone to landslides, such as the clay rich regions of the St. Lawrence valley, where soil characteristics interact with land use and exacerbate the vulnerability of rail transportation systems.

Similar to road transportation, rail transportation is vulnerable to impacts from forest fires caused by lightning. The economic impact of fires is particularly significant for the network in the center of the province, where there is little redundancy. In 2013, Arcelor Mittal Mines Canada, which uses rail tracks in Quebec and has three camps for its staff, saw its operations restricted for several days near Manic-Cinq due to fires and smoke. Access to industrial sites, including those for general maintenance activities, was restricted by near zero visibility conditions. Decreased visibility created by bad weather (fires, heavy rains, etc.) also makes operating a locomotive more complex and dangerous.

Changes in freeze-thaw cycles also affect track integrity and can reduce the lifespan of infrastructure. They can also trigger landslides, which is particularly problematic on tracks where required clearances around the infrastructure are minimal.

Tracks undergo a certain expansion during times of extreme heat and a certain contraction during deep freezes, but generally react well to temperature variations. However, in the context of significant thermal variation, this expansion phenomenon can damage tracks.

4.3.1 RAIL TRANSPORTATION IN THE ST. LAWRENCE CORRIDOR

Bank erosion, flooding and submersion problems, phenomena heightened by climate change, affect coastal train tracks such as the Charlevoix Railway Inc. and the Gaspé Railway Company, as well as railways located along streams, like the Compagnie de chemin de fer de l'Outaouais and the Chemin de fer Québec Central. Erosion can compromise network structural integrity, and even cause a complete interruption of activities in the affected region. A landslide in Gascons on the Gaspé Peninsula suggests such rail network vulnerabilities in this region (Locat et al., 2013). Furthermore, in the Charlevoix and North Shore areas (around Sept-Îles particularly), some track segments are affected by challenges related to slope stability, geotechnical issues, or rockfall (Leroueil et al., 2001).

4.4 AIR TRANSPORTATION

Meteorological conditions, including localized events such as strong winds, thunderstorms and heavy precipitation, influence flying conditions throughout Quebec. Combinations of multiple events, such as freezing rain followed by strong winds, complicate take-offs and landings.

In southern Quebec, air transportation involves multiple national and international connections for passengers and goods. As a reduction in the duration and frequency of freeze-thaw events is expected in southern Quebec, runway and aircraft maintenance needs and associated costs could be reduced (Mills, 2004), which would be positive for air transportation in the region.

Nevertheless, an increased frequency and intensity of extreme weather events could increase the frequency of flight delays and cancellations, limiting the mobility of passengers and goods.

Villages in Nunavik, those on the Magdalen Islands, and those in the far east of the North Shore are particularly vulnerable to disruptions in air transportation, as they rely heavily on this mode for inter-regional travel.

Airport infrastructure in Nunavik was designed between 1984 and 1991 for a stable climate with no special measures to protect against permafrost thaw (Guimond et al., 2010). However, rising temperatures, and in some cases increased precipitation and runoff, are contributing to permafrost thaw, resulting in differential soil settlements, and premature damage to infrastructure. Snow accumulation along runways and embankments serves as an insulator and warms the ground, also contributing to thaw (Savard, 2006; Guimond and Boucher, 2013). Some infrastructure is showing signs of deterioration attributable to permafrost thaw (Guimond et al., 2010). Access roads and landing strips in this region could see their lifespan diminish and thus compromise emergency management and services, and require additional maintenance work. Freeze-thaw events in this region further complicate de-icing and increase maintenance costs for landing strips.

Extreme weather events also contribute to the vulnerability of air transportation in Nunavik. Although few studies have been done on wind, the Quaqtamiut note [translation] "[...] a worsening of strong winds and storms in past years" (Clerc et al., 2011). In addition, flight time and, consequently, fuel consumption, fluctuate based on winds (Morris, 2011).

Finally, the Société de protection de la forêt regularly flies over central Québec as well as other commercial airlines that have connecting flights between the south and north of the province. Air transportation is sensitive to extreme weather events. A projected increase in the occurrence of such events would increase runway maintenance needs and, as a result, costs associated with labour, rental, machinery and products needed to address them. In addition, forest fires and smoke considerably reduce visibility for planes, which must adapt their flying methods to ensure safety (Transport Canada, 2015, p. 211).

4.5 DISTRIBUTION AND TELECOMMUNICATION NETWORKS

Transport and mobility depend greatly on information technology and communications systems. Information and telecommunication networks can be affected by strong winds, thunderstorms, lightning, and ice. Although it is difficult to know how climate change will modify the frequency or intensity of specific conditions, breaches and breakages caused by these events are likely to affect the entire transportation system. The ice storm in southern Quebec in 1998 illustrates the cascading effects a disruption due to extreme weather can have on various networks (telecommunications, services, electricity, etc.) and thus on the entire transportation system (Dupigny-Giroux, 2000).

5.0 ADAPTATION MEASURES

Climate change affects all regions of Quebec without concern for administrative limits or shared jurisdictions, and depends on the collaboration of various levels of government and Quebec's civil society (Ouranos, 2015).

Climate change will have both positive and negative effects on construction costs and the lifespan of land-based infrastructure (Doré et al., 2014). Several actions can contribute to making infrastructure more resilient. Above all, it is important to consider a set of complementary measures. Changing design can improve (or maintain) structural performance. However, increased maintenance activities and methods to detect early failure can help significantly reduce vulnerability. It is also important to pursue work that evaluates the technical, economic and environmental performance of potential adaptation measures (Doré et al., 2014; Ouranos, 2015).

This section reviews plans and projects implemented over the last several years by the Quebec government, regional and local organizations and authorities, and transportation companies. There is relatively little documentation on actions planned or implemented by the private sector to adapt Quebec's transportation infrastructure, management and planning systems to climate change.

5.1 ADAPTATION MEASURES PLANNED AND IMPLEMENTED BY THE QUEBEC GOVERNMENT

In 1996, the Quebec government developed its first Climate Change Action Plan (CCAP), which equipped government authorities to better understand climate risks in Quebec. The CCAP developed for 2006-2012 ($99 million) aimed to provide government stakeholders, the scientific community and non-governmental organizations the means to implement actions to reduce greenhouse gas emissions and to adapt to climate change (Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, 2015). Among the 26 measures of this action plan, Measure 23 was specifically related to transportation, and gave the MTMDET the mandate of evaluating and conducting research that helped better understand phenomena that could affect the Quebec transportation system. Studies conducted during this period improved understanding of the coastal environment and how it might change due to the effects of climate change, and considered the challenges of erosion and flooding within the long-term management of exposed infrastructure. Other studies helped better define issues concerning permafrost thaw and integrate appropriate strategies for the design, repair and management of infrastructure.

In 2012, the Quebec government adopted a Government Strategy for Climate Change Adaptation 20132020 (Gouvernement du Québec, 2012a). The Strategy aims to raise public awareness of climate change and mobilize several departments and partners, including the MTMDET, regarding the sustainability and adaptation of transportation infrastructure. To improve services offered to the public and to adapt transportation, the 2013-2015 MTMDET strategic plan for MTMDET supports diversifying modes of transportation. Consideration of climate change is a major part of the plan (MTQ, 2012).

The importance of transportation is also recognized in the current action plan on climate change entitled « Le Québec en action vert 2020 » "Quebec Green Action 2020" (Gouvernement du Québec, 2012a). This plan, based on the Government Strategy for Climate Change Adaptation (Gouvernement du Québec, 2012a), supports crosscutting actions specific to health, the economy, infrastructure and the natural environment. Land-use planning is a key element of the plan, aimed at strengthening community resilience. Urban densification is identified as a tool for reducing future infrastructure needs, including roads (Gouvernement du Québec, 2012a; 2012b). Communication among residents and public and private stakeholders is also identified as a cross-cutting action to support climate change adaptation. Moreover, the plan provides for "specific training, awareness-building, knowledge transfer and decision support tools, and technical assistance [...] to targeted audiences" (Gouvernement du Québec, 2012a). Efforts on this element have already been launched, specifically for government employees.

5.2 ADAPTATION MEASURES ON A REGIONAL AND LOCAL SCALE

Local knowledge and community involvement are also important. Knowledge and stories about changes to modes of travel and traditional routes help identify changes to the climate that are otherwise difficult to document (Grimwood et al., 2012; Samson et al., 2013).

Significant progress (action, research, awareness-raising) has been made in the last ten years to promote anticipatory adaptation (Cuerrier et al., 2015; Bernatchez et al., 2012; Plante et al, 2015). In northern Quebec for example, adaptation measures were implemented when the first signs of deterioration to transportation infrastructure were observed, before significant climate impacts were felt (Guimond et Boucher, 2013).

Since 2003, the MTMDET has had a thermal monitoring program for airport infrastructure in Nunavik (under its jurisdiction), built on land sensitive to thaw (Guimond et Boucher, 2013). In the last decade, mapping of permafrost areas in northern communities has been undertaken to support land-use planning (L'Hérault et al., 2013). By using data from geotechnical research, such mapping determines which areas to avoid, which require more information, and which require special construction techniques to address problem areas identified. A better understanding of constraints helps prioritize procedures for the area, based on existing knowledge (L'Hérault et al., 2013; also see Case Study 2).

In 2007, 12 communities were the subject of a soil classification project led by the Center for Northern Studies, and other more detailed studies are underway (Allard, Calmels, et al., 2007; L'Hérault et al., 2013). More specifically, the impact of a changing climate on landing strip stability in Nunavik has been the subject of several studies since the early 2000's (Allard, Fortier, et al., 2007; Doré et al., 2014; Allard et al., 2013.) Researchers have identified methods of intervention to maintain air operations, including more frequent maintenance and improvements to drainage techniques (L'Hérault et al., 2013).

The MTMDET and the Center for Northern Studies recently collaborated in the development of an adaptation strategy for airport structures vulnerable to permafrost thaw (Guimond et al., 2010). Temperature monitoring devices were embedded at 13 airports in Nunavik to monitor the condition of runways in real-time. Adaptation techniques were tested on two problem sites (see Case Study 1). The Kuujjuaq landing strip was the subject of a study by Transport Canada, while more generally, regular monitoring is undertaken to verify the condition of transportation facilities (airports, access roads and marine infrastructure).

In addition, each municipality is developing a land-use master plan that identifies the areas suitable for building in order to ensure the sustainability of transportation infrastructure and operations (L'Hérault et al., 2013). Awareness tools and best practice guides have also been developed by municipal authorities in order to inform employees and suggest concrete actions to reduce the impact of climate change on infrastructure (for example, drainage and snow management on land infrastructure).

CASE STUDY 1

CASE STUDY 1: MONITORING THE THERMAL BEHAVIOUR OF THE SALLUIT AIRPORT ACCESS ROAD AND TESTING A METHOD TO DETECT PERMAFROST DEGRADATION ALONG LINEAR STRUCTURES IN THE CONTEXT OF CLIMATE CHANGE

A section of the Salluit Airport access road in Nunavik is built on permafrost made up of ice-rich marine deposits. Since the early 2000's, researchers have observed significant degradation linked to permafrost thaw in this section. In 2012, the MTMDET proceeded with the reconstruction of this section of road in order to maintain safe land access year-round, in the context of a changing climate. The embankment design was adapted by integrating it with new design criteria that aimed to promote a rise in the permafrost table. Within the framework of this project, two technological innovations were tested: the use of fiber optic cable to detect sectors at risk of deterioration along the road, and the implementation of an embankment with a large scale heat sink as an adaptation solution. This project was undertaken by the MTMDET, in collaboration with the Center for Northern Studies and the Laval University surface engineering research group. http://www.mddelcc.gouv.qc.ca/changementsclimatiques/bilan-2012-2013/adaptation.htm

Monitoring the state of the environment and infrastructure is important and several management measures (e.g., snow removal along roads; more frequent cleaning of culverts; identification of alternative routes) and design measures (e.g., lessening the slope of the dyke; replacing culverts) can be implemented to reduce the impact of climate risks (Transportation Association of Canada, 2010). See the chapter on the Northern Territories for additional information on maintenance, monitoring and construction practices aimed at maintaining the integrity of infrastructure built on permafrost.

CASE STUDY 2

CASE STUDY 2: DAM BREAK AND FLOODING OF THE SAGUENAY

In 1996, heavy rains hit the Saguenay region of Quebec. A series of floods forced the evacuation of 16,000 people and destroyed several roads and bridges, isolating some populations.

Following these events, the Centre de géomatique du Québec (Quebec Geomatics Center) and the Ministère de la Sécurité publique (Department of Public Safety) implemented an interactive on-line mapping tool (GéoRISC portal) to guide dam managers and limit the consequences of dam breaks and flooding in the region. This management system (SCORE) has been online since 2008, providing continuous access to descriptive data for dams in Saguenay-Lac-Saint-Jean. Among other uses, modelling with this data makes it possible to consider the consequences of a dam collapse, recognize the impact that precipitation has on the road system, and plan alternative routes.

A research chair in coastal and fluvial engineering was created in 2013 (Gouvernement du Québec, 2012b). This chair, created within the Institut national de la recherche scientifique (INRS), with the collaboration of the MTMDET and MSP, has conducted various research projects on the adaptation of design criteria for coastal remedial works (Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, 2014). In addition, studies on the vulnerability of road infrastructure in eastern Quebec were conducted by the chair in coastal geoscience at the Université du Québec in Rimouski (Drejza et al, 2014; Drejza et al, 2015.).

Ongoing efforts to model the hydrology of the St. Lawrence drainage basin are helping to plan for the impact of climate change on hydrological systems influencing marine transportation (Bouchard et Cantin, 2015). However, port authorities and marine industry representatives appear less equipped to anticipate extreme weather events such as storms, hurricanes, etc., that will have a greater effect on their operations in the coming years (Slack and Comtois, 2016).

Following a study by INRS (Mailhot et al., 2014), as of 2015 the MTMDET has applied a new loading factor of 18 or 20% for watershed flows of 25 km^2, depending on the region of Quebec, to account for climate change (MTMDET 2015). This adjustment factor was 10% until recently. The use of the GéoRISC portal also contributed to dam management (see Case Study 2).

On a more local level, several studies (see summary in Savard et al., 2008) led jointly by the Ministère de la Sécurité publique, the Université du Québec à Rimouski, Ouranos and the City of SeptÎles, contributed to a better understanding of the causes and factors associated with coastal erosion. The municipality of Sept-Îles then zoned its territory to better control usage along the shoreline and performed a cost-benefit analysis of various solutions for structures already threatened by the loss of coastal terrain. The City of Sept-Îles, where roads are seriously affected by bank erosion, has implemented a sand refill strategy for those beaches that are most threatened by erosion. It has also prohibited riprap in several areas.

Although it is included on a list of remedial works to prevent road erosion, riprap may be less advantageous from an economic and structural perspective than alternative protection options depending on the nature of the coast (Bernatchez and Fraser, 2012). Similarly, because sand refill, riprap and oversizing alone cannot ensure the resilience of coastal areas to heightened erosion and an increased frequency, duration and intensity of extreme weather events, the City of Sept-Îles is working with the SeptRivières RMC and the Quebec government to come up with a plan for coastal procedures (Natural Resources Canada, 2015). This plan will help determine the sectors most at risk and consider various scenarios for transferring equipment and infrastructure.

The procedural plan for emergency management in the Magdalen Islands identifies buildings and roads at risk of erosion. It presents scenarios for interventions as well as transferring infrastructure and equipment, and identifies potential partners, including the MTMDET. The plan also highlights municipal willingness to integrate an "appropriate city regulation" into the city plan (Municipality of the Magdalen Islands, 2010).

With respect to fires and their impact on roads, a study on lightning was conducted in Quebec by the Canadian Forest Service (Morrissette, 2009). It made it possible to localize events and determined that lightning density is higher in the southern and western regions of the province. In 2005, a drought resulted in numerous forest fires, forcing the emergency evacuation of nearly 1,000 residents in the City of Chibougamau (Gouvernement du Québec, 2005). The MTMDET collaborated with the Société de protection des forêts contre le feu and municipalities in central Quebec to improve knowledge regarding climate hazards, including forest fires, and associated transportation vulnerabilities; to develop decision-making tools; and, to prepare land-use plans aimed at ensuring the sustainability of transportation infrastructure and services.

6.0 CONCLUSIONS AND FUTURE RESEARCH NEEDS

Transportation networks play a critical role in supporting economic competitiveness and quality of life. However, the high level of interdependence among systems renders the challenges associated with climate change more complex (Ouranos, 2015).

Climate change will modify the natural environment in all areas of Quebec. Most of Quebec's coastal areas will experience an increase in erosion, in addition to flooding in areas that were minimally affected until now.

In Nunavik, thawing permafrost contributes to the collapse and cracking of roads and airport infrastructure, which are essential to serving the communities (Transport Canada, 2015). Maintenance techniques and rehabilitation, as well as the frequency of interventions, must be modified resulting in significant additional costs and challenges for planning. In this region of Quebec, changes in ice cover and changes in storm regimes also significantly affect winter mobility. Management of runoff and drainage are also affected by climate change. Maps characterizing permafrost areas can help to better plan development, and are an important tool to protect infrastructure in this region. Many challenges remain in the area of northern infrastructure adaptation, particularly in relation to knowledge transfer, acquisition of long-term data, the use of new technologies to optimize data acquisition, and interventions (Transport Canada, 2015).

In urban areas, frequent and more intense rains cause local flooding and will likely increase with climate change. A combination of measures would help better manage stormwater issues.

Extreme weather events appear to pose the greatest risk for infrastructure and transportation systems in all seasons. Infrastructure design, along with all aspects of operation, maintenance, management and refurbishment is, and will continue to be, affected by climate change.

Adaptation is a social and institutional challenge that should be treated in an integrated fashion. The impact of climate change on infrastructure cannot be studied in isolation from other factors (social, political, cultural, environmental and economic) that influence infrastructure usage and management. Local and global vulnerabilities of the Quebec transportation system must be recognized in order to develop relevant adaptation tools and measures that help maintain the condition of infrastructure and transportation operations.

The Quebec government has dedicated considerable efforts over the last two decades to better understanding the impact of climate change on the natural environment as well as on transportation infrastructure and mobility. The challenges related to storm water management such as bank erosion and permafrost thaw are particularly well documented. Strategies to develop solutions to these problems are becoming better understood. On the basis of this work, the government has started to implement concrete actions to increase overall resilience. Nevertheless, transportation adaptation continues to be a subject requiring further research.

There is also a need to better document climate risks to organizations, companies and operating systems. Understanding the interaction between natural environmental changes caused by climate change and the design, organization and management of transportation systems could benefit from more studies.

With respect to road transportation, more research is need for the coordination between different stakeholders and assessments of the impact of climate change on road signalling and peripheral equipment, as well as on the use and development of informal roads and corridors in the North.

As for rail transport, few studies were identified. Therefore, it remains difficult to determine specific rail transportation challenges in Quebec.

In the area of marine transportation, there is a need to improve and further document knowledge of the vulnerability of infrastructure and marine transportation to climate change, especially in southern Quebec. Several themes are worth looking into, such as: assessing premature damage to infrastructure associated with climate change; and studying the combined impact of increased navigation and climate change on invasive marine species.

With respect to electrical transmission and distribution, the thresholds and tolerance levels of equipment and infrastructure to hostile conditions (strong winds, lightning, freezing rain, etc.) need to be determined. This can help prevent disruption to communications systems in transportation infrastructure such as the fibre optic cables used in the Arcelor Mittal railway damaged due to heavy rain.

Finally, monitoring the condition of infrastructure relative to a well-documented baseline condition would help improve the understanding of potential vulnerabilities, evaluate the performance of measures implemented, and intervene in a more intelligent and strategic manner in problem areas. Thus, long-term data collection is important both to continue to document the impact of climate change, and to define design criteria and best practices for maintenance and management. Enhanced knowledge also allows for the exchange of best practices regarding infrastructure design, construction and maintenance.

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CHAPTER 8:
ATLANTIC CANADA

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TABLE OF CONTENTS

KEY FINDINGS

- **The climate risks of greatest concern to transportation operators, provincial governments, and municipalities in Atlantic Canada are extreme weather events and storm surges.** Hurricanes, high winds, heavy precipitation, and extreme snowfall have resulted in costly damage and shipping disruptions for marine ports, delayed flights and ferry services and washed-out roads and railways. As storm frequency and intensity increases, these impacts will likely continue to be severe.

- **While most actions to enhance the climate resilience of transportation systems have been taken in response to past impacts from extreme weather, future climate risks (such as sea level rise) are increasingly spurring planning and investments**. Coordinated partnerships and initiatives suggest Atlantic provinces are actively engaged in adaptation planning. Risk assessments and regional cost-benefit analyses, which include transportation systems within their scope, will help inform future decision-making.

- **Transportation practitioners are accounting for projected climate changes in the planning and operation of some roads, bridges, railways, and marine ports in Atlantic Canada, but actions related to airports are less well-documented.** While this is reflective of the dominance of road and marine transportation in the region, significant research gaps exist regarding adaptation strategies for all modes.

- **A number of strategies are being specifically used to enhance the resilience of transportation infrastructure to flood risks**. These include constructing physical barriers (seawalls, breakwaters, and dykes), improving stormwater management (updating design flows, enlarging culverts) and relocating and/or elevating infrastructure.

- **Regionally-focused weather- and climate-monitoring technologies are helping transportation operators identify and adapt to climate risks in Atlantic Canada.** Examples include SmartAtlantic monitoring buoys to inform extreme-weather preparedness and better understand changes in ocean climate, and the Coastal Impact Visualization Environment (CLIVE) tool, which allows users to visualize changing coastlines in Prince Edward Island. These technologies assist with risk assessment and help practitioners communicate the magnitude of short- and long-term impacts to decision-makers.

1.0 INTRODUCTION

Atlantic Canada includes the provinces of New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador. While each province has unique geographic and cultural characteristics, their shared proximity to the Atlantic Ocean and combined coastlines (exceeding 40,000 km) (Environment Canada, 2012) result in many common climate vulnerabilities for transportation systems. These include risks associated with both extreme weather events (e.g., flooding, seasonal storms) and gradual, long-term changes (e.g., sea-level rise, changing patterns of temperature and precipitation). Governments and the private sector have recognized the need for adaptive action to reduce losses, avoid future costs, and benefit from potential opportunities.

This chapter examines the risks and opportunities for Atlantic Canada's transportation sector, as well as practices to increase its resilience to a changing climate. It addresses all four major transportation modes (roads, rail, marine, and air).

Literature examining the impacts of climate on transportation systems in Atlantic Canada is quite limited. Therefore, this chapter draws heavily upon other sources of information, including interviews with transportation professionals. This research complements other assessments of climate impacts and adaptation for Atlantic Canada as a whole (Vasseur and Catto, 2008) and the Atlantic coast more specifically (Savard et al., 2016).

1.1 ENVIRONMENTAL CHARACTERISTICS

Atlantic Canada has a diversity of landscapes, including five distinct terrestrial ecozones (Environment Canada and Agriculture and Agri-Food Canada, 1999). Prominent landforms include rugged mountains (e.g., the Torngat Mountains in Labrador), fertile valleys (e.g., the Saint John River Valley in New Brunswick and the Annapolis Valley in Nova Scotia), and extensive coastlines. The interior regions of New Brunswick, Nova Scotia, and Newfoundland and Labrador are dominated by rolling to rugged uplands, and are much more sparsely populated than the coasts.

Climate regions range from cool humid-continental to Arctic tundra, with the influence of the warm Gulf Stream in the south giving way to the cold Labrador Current in the north. Seasonal conditions reflect competing tropical and polar, and continental and maritime, influences. The Atlantic coasts experience the full range of tropical and extra-tropical storm systems frequently associated with high winds, precipitation, and storm surge.

1.2 DEMOGRAPHIC CHARACTERISTICS

Atlantic Canada is home to approximately 2.4 million people. The region experienced modest population growth from 2006 to 2011 (a provincial average of 2.2 percent), although at lower rates than the national average (5.9 percent) (Statistics Canada, 2011). Population shifts within the region demonstrate significant migration from rural areas to urban centres, with much greater population growth in major cities (see Table 1).

Table 1: Population and population changes in Atlantic provinces and census metropolitan areas (CMAs). (Source: Statistics Canada, 2011)

Location	Area (km^2)	2011 Population	2006 Population	Population growth 2006-2011
New Brunswick	73,440	751,171	729,997	2.9 %
Newfoundland & Labrador	405,720	514,536	505,469	1.8 %
Nova Scotia	55,490	921,727	913,462	0.9 %
PEI	5,590	140,204	135,851	3.2 %
Halifax CMA	5,490.28	390,328	372,858	4.7 %
St. John's CMA	804.65	196,966	181,113	8.8 %
Moncton CMA	2,406.31	138,644	126,424	9.7 %
Fredericton CMA	4,886.40	94,268	86,226	9.3%
Saint John CMA	3,362.95	127,761	122,389	4.4%
Charlottetown CA	798.54	64,487	59,325	8.7 %

1.3 ECONOMIC CHARACTERISTICS

The majority of trade in Atlantic Canada is conducted with partners outside of the region – primarily with the United States and other provinces, although international markets are becoming more important.

Almost half of all freight traffic originating from New Brunswick and Nova Scotia is destined for other provinces, while less than 25 percent is intra-provincial (Gauthier, 2014). Prince Edward Island shares a similar freight pattern, with the majority of exports distributed across Canada. Newfoundland and Labrador is more closely connected to global supply chains than other Atlantic provinces, with approximately one-third of freight traffic destined for the United States, and one-third destined for the rest of the world (Lambert-Racine, 2013).

The Atlantic region is North America's closest access point to Europe, and major ports in New Brunswick, Nova Scotia, and Newfoundland and Labrador play an important role (Canada's Atlantic Gateway, 2010). The regional economy is positioned for further growth in global trade, including increasing connections with emerging Asian markets through the Suez Canal. These trends are already underway – for example, the values of exports from Newfoundland and Labrador to China, the United Kingdom, Netherlands and France increased by more than 400 percent from 2010 to 2013 (Newfoundland and Labrador Statistics Agency, 2015). As trade activity along many regional and external routes expands, transportation operators are working to provide the capacity to meet this demand.

Key exports from the Atlantic region include crude oil and refined energy products, fish, shellfish, minerals, lumber and pulp products, potatoes, and other vegetables. Key imports include many of these same commodities, as well as machinery/mechanical parts (Atlantic Canada Opportunities Agency, 2012).

2.0 REGIONAL CLIMATE PROFILE

2.1 OBSERVED CLIMATE TRENDS

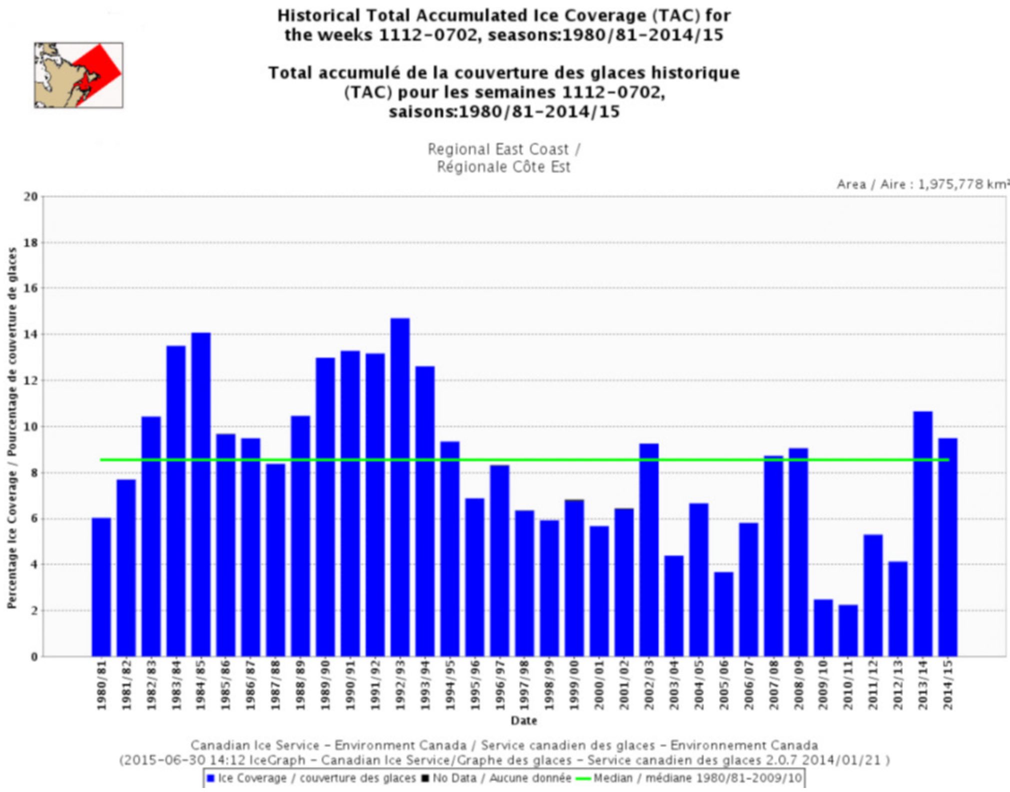
Atlantic Canada's historic climate record is characterized by high year-to-year variability, as well as variability in long-term trends (over several decades) in several key climate parameters. For the period 1948-2014, mean annual temperature in the Atlantic Canada Climate Region[4] increased 0.7°C, similar to the global average for the same period and representing the least amount of warming of any Canadian region (Environment Canada, 2015a). Increases have also been observed in sea-surface temperatures and ocean acidity (Loder et al., 2013). No clear trend is evident for mean annual precipitation in the region, although both summer and fall have experienced precipitation increases (Mekis and Vincent, 2011).

Of greater interest to Atlantic Canada's transportation system are changing patterns of extreme weather, such as heavy precipitation and seasonal storms. These events increase flood risks (both inland and coastal), and exacerbate issues in areas prone to erosion. Due to the rarity of extreme weather events, it is difficult to identify trends in the historic record, particularly at the regional scale. For example, from 1950-2010 the occurrence of heavy precipitation shows a statistically significant increase at some locations in Atlantic Canada, but a decrease at others (Bush et al., 2014). While changes in average wind speeds and direction are absent from the historic record, analysis of the density of intense storm centres for the period 1961-2000 indicates that Atlantic Canada includes some of the stormiest areas in North America (Savard et al., 2016). While the frequency of North Atlantic hurricanes shows no long-term significant change (United States Environmental Protection Agency, 2015), the Intergovernmental Panel on Climate Change's Fifth Assessment Report (2013) and the United States Global Change Research Program (2014) note that hurricane intensity has increased in the Atlantic region since the 1980s.

Changes in sea ice cover and sea levels have implications for marine and coastal transportation infrastructure. Sea ice coverage has decreased significantly in recent decades, although inter-annual variability remains high (Figure 1). Reduced sea-ice cover makes coasts more vulnerable to erosion by waves during winter storms. Trends in relative sea level for most of Atlantic Canada, excluding Labrador, show slow and steady sea-level rise. This increase is primarily due to glacial isostatic adjustment in the Atlantic provinces, referring to the slow vertical land motion or "rebounding" of land depressed by hundreds of metres under ice sheets during the most recent ice age (James et al., 2014). Sea-level rise results in impacts from waves and storm surge at higher coastal sites not previously at risk (Atkinson et al., 2016).

[4] Including New Brunswick, Nova Scotia, Prince Edward Island, and the island of Newfoundland, but excluding Labrador.

Figure 1: Historical total accumulated ice coverage for the weeks of December 11-February 7 from 1980 to 2015 in Atlantic Canada and the St. Lawrence estuary (see inset map). (Source: Environment and Climate Change Canada)



2.2 FUTURE CLIMATE PROJECTIONS

Projected changes in climate in Atlantic Canada for the 21st century include continued warming of air and water temperatures, as well as increased precipitation. Recent analysis as part of a global climate model comparison project[5] suggest increases in mean annual temperature of 1°C in the near term (2016-2035) to about 3°C by the end of the century. The greatest warming is projected to occur in winter. Mean annual precipitation is projected to increase by about 3 percent in the near term and almost 10 percent by the end of the century throughout the region, with the greatest increases occurring in winter and spring. Snowfall is likely to comprise a reduced proportion of total precipitation; the seasonal duration of snow cover will likely decrease (Swansburg et al., 2004); and freezing rain events are likely to increase during winter (Cheng et al., 2011). Tables A1-A4 (located in the annex of this chapter) present provincially-specific temperature and precipitation projections for the Atlantic region to 2100 over three time horizons. Seasonal periods include winter (December-February), spring (March-May), summer (June-August), and autumn (September-November). Data was derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate model under an ensemble of RCP2.6, RCP4.5, and RCP8.5 scenarios (Canadian Climate Data and Scenarios, 2015). These data reflect uncertainty associated with these projections by presenting a range of values from the 25th-75th percentiles of CMIP5 outputs. The median value (50th percentile) appears in brackets following the range.

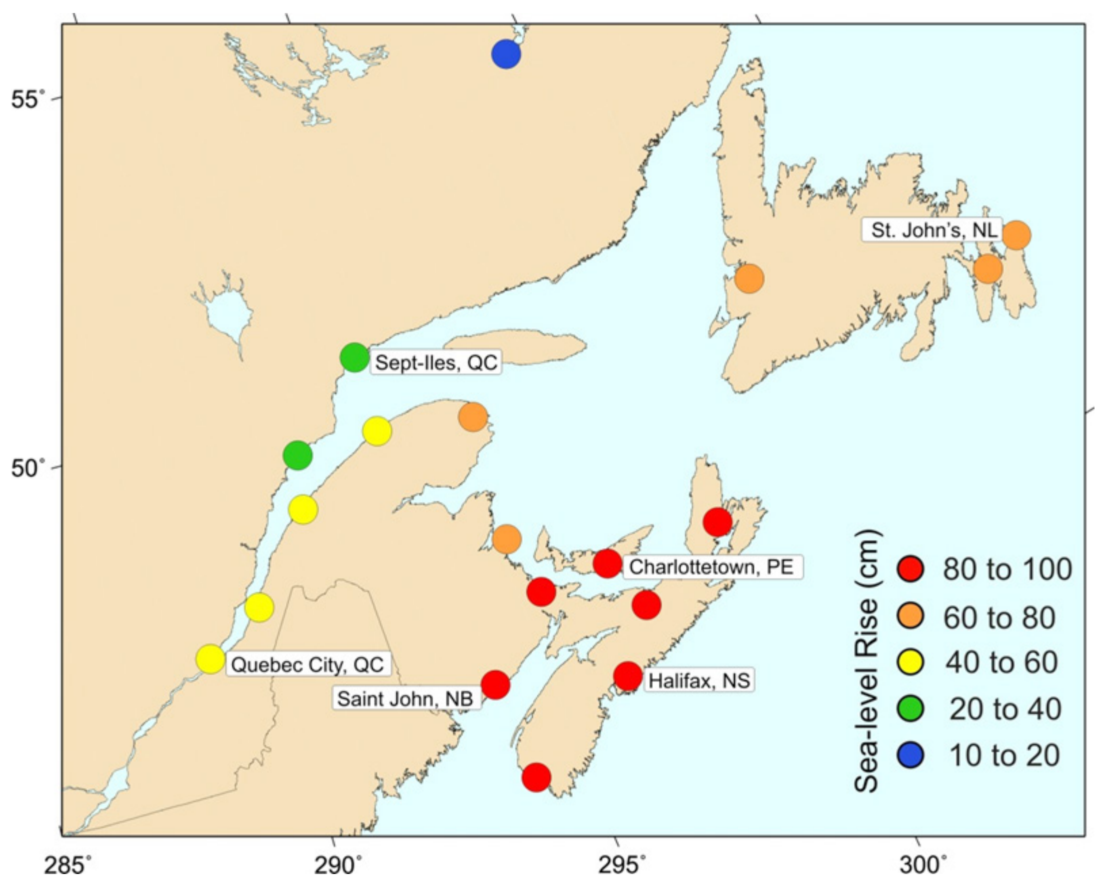
5 CMIP5 - Coupled Model Intercomparison Project, Phase 5 (Taylor et al., 2012).

Global projections forecast an increasing frequency of extreme heat and decreasing frequency of extreme cold in Atlantic Canada (Williams and Daigle, 2011). Extreme precipitation events are also likely to become more frequent (Swansburg et al., 2004). Significant changes in wind speeds are not anticipated, but there is likely to be a northward shift in storm tracks through the current century, increasing storm frequency in Atlantic Canada (Loder et al., 2013).

Sea ice will continue to decrease in extent, thickness, concentration, and duration, with models projecting that it will be almost completely absent in the Gulf of St. Lawrence by 2100 (Senneville et al., 2013).

In areas of Atlantic Canada currently experiencing sea-level rise, the rate of change will accelerate throughout the current century. In areas such as Nain, Labrador, where sea level is currently falling due to glacial isostatic rebound, sea level will either continue to fall at a slower rate, or it may start to rise, depending on the magnitude of change in global mean sea level (James et al., 2014). Projections for Atlantic Canada indicate that under a high-emissions scenario, up to 100 cm of sea level rise is possible at some locations by 2100 (Figure 2), and that larger increases cannot be precluded (Savard et al., 2016; Atkinson et al., 2016). Global mean sea level will continue to rise for centuries after 2100, with the magnitude of future changes influenced by the success of efforts to reduce global greenhouse gas emissions (Intergovernmental Panel on Climate Change, 2013).

Figure 2: Projections of relative sea-level rise for the year 2100 for the median value of the high-emissions scenario (RCP8.5; after James et al., 2014). See Atkinson et al. (2016) for additional information on sea-level projections, and Savard et al. (2016) for additional details on sites in Atlantic Canada. (Source: Natural Resources Canada)



An important consequence of sea-level rise is the extreme water levels associated with wave run-up (also referred to as "swash," the height above the still-water elevation of the sea) and storm surge (the difference between observed water level and the predicted astronomical tide, resulting from variations in atmospheric pressure and wind). Sea-level rise will result in both more extensive storm-surge flooding, and increased frequency of events that contribute to coastal flooding and erosion. For example, analysis for Halifax Harbour indicates that a 40 cm rise in sea level by 2050 will yield drastic changes in extreme water levels – by mid-century, storm surges which currently have a return period of once in 50 years are likely to occur (on average) more than once every five years (Forbes et al., 2009).

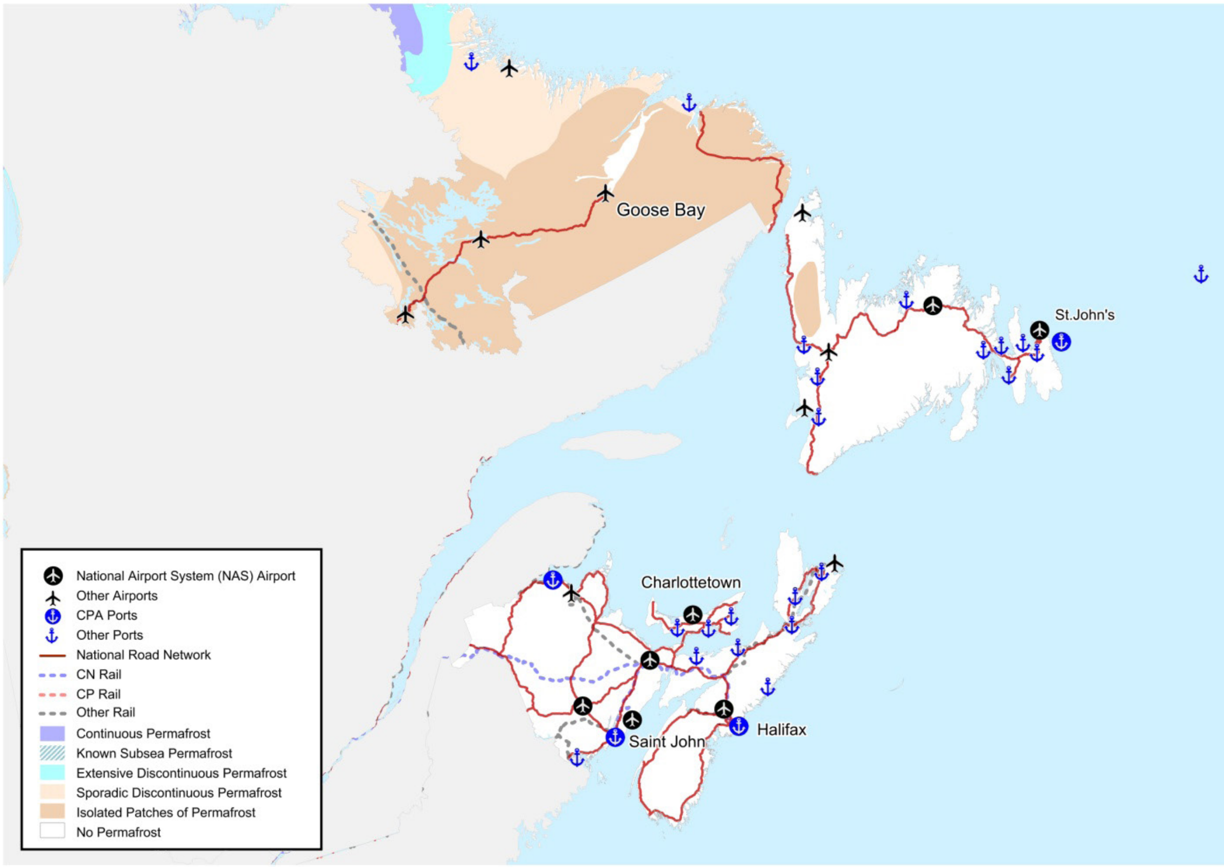
3.0 ATLANTIC CANADA'S TRANSPORTATION SYSTEM

The following sections discuss the physical assets and operations for each mode of transportation in Atlantic Canada, with an overview in Table 2, and an illustration of principle networks in Figure 3.

Table 2: Transportation assets in each Atlantic province. (Source: New Brunswick Department of Transportation and Infrastructure, 2014; Newfoundland and Labrador Department of Transportation and Works, 2014; Nova Scotia Department of Transportation and Infrastructure Renewal, 2015a; Prince Edward Island Department of Transportation and Infrastructure Renewal, 2012; Province of Nova Scotia, 2009a; Railway Association of Canada, 2015; Transport Canada, 2014)

Transportation assets	New Brunswick	Newfoundland and Labrador	Nova Scotia	Prince Edward Island
Highways and provincial roads (km)	18,785	9,759	23,000	3,849 paved 1,521 unpaved
Bridges	3,212	1,327	4,100	257
Canadian Port Authorities	Saint John and Belledune	St. John's	Halifax	n/a
Ferries and Terminal Ports	10 crossings 18 terminal ports	18 crossings 40 terminal ports	7 provincial 2 municipal 5 private 39 terminal ports	2 crossings 2 terminal ports
Rail (km)	1159	261	674	No rail services
Airports	3 NAS Airports (Fredericton, Moncton, Saint John) 3 Regional/Local (Charlo, Chatham, St. Leonard)	2 NAS Airports (Gander, St. John's) 6 Regional/Local (Churchill Falls, Deer Lake, Goose Bay, Stephenville, St. Anthony, Wabush)	1 NAS Airport (Halifax) 2 Regional/Local (Sydney, Yarmouth)	1 NAS Airport (Charlottetown)

Figure 3: Principle transportation networks in Atlantic Canada.

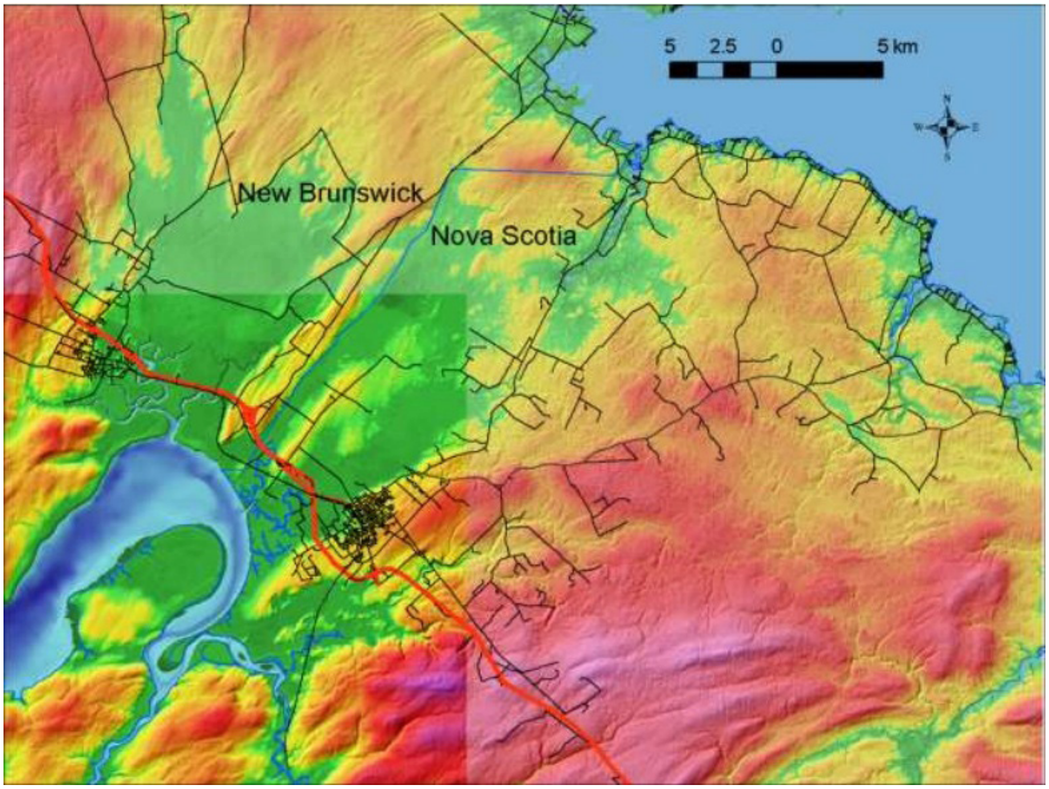


3.1 ROAD AND RAIL TRANSPORTATION

Atlantic Canada's extensive surface transportation infrastructure (road and rail) reflects its regional importance in moving people and goods. Each Atlantic province is reliant on roads, while rail plays a very significant economic role in Nova Scotia and New Brunswick in the form of the CN Rail system that crosses the Chignecto Isthmus. About $19.5 billion in trade flows annually by rail across the Isthmus, which represents about 45% of the total annual trade movements throughout Atlantic Canada (Webster et al., 2012; Marlin, 2013). The corridor is the only land connection between Nova Scotia and New Brunswick, and is highly vulnerable to storm surge and sea level rise (Figure 4; also see Case Study 5). A system of dykes, which includes rail embankments in some stretches, was originally built by the Acadians to create agricultural land and currently protects land and rail, road and other infrastructure in the Isthmus (Webster et al., 2012).

A second important rail link in Atlantic Canada is a short section of rail in Labrador that connects to the Quebec North Shore and Labrador Railway (QNS & L). The shipment of iron ore from Labrador via the QNS & L represents the largest component of total commercial rail tonnage moving out of Atlantic Canada (Stassinu-Stantec Limited Partnership, 2011). Prince Edward Island and the island of Newfoundland do not have operational rail lines, while a few independently-owned short-line systems operate in New Brunswick and Nova Scotia.

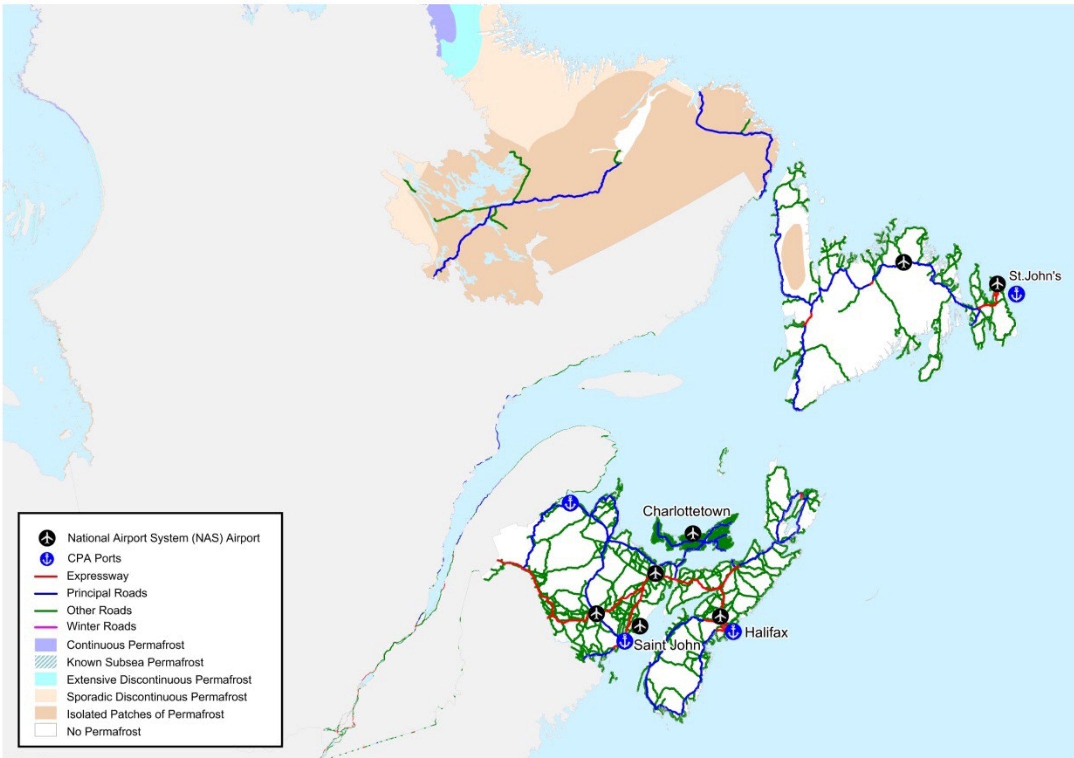
Figure 4: Colour-shaded relief digital elevation model of the Chignecto Isthmus at the New Brunswick-Nova Scotia border. Green depicts especially low-lying areas. The Isthmus separates the Bay of Fundy to the southwest from the Northumberland Strait (Gulf of St. Lawrence) to the northeast. (Source: Applied Geomatics Research Group, Nova Scotia Community College)



Large freight volumes are also moved by truck in Atlantic Canada. While the majority is destined for other Canadian provinces, a significant portion is also shipped to the United States (crossing primarily at Woodstock and St. Stephen, New Brunswick (Transport Canada, 2014). Major highways and connector roads also link cities, towns, and provinces in Atlantic Canada (see Figure 5).

St. John's, Newfoundland is the easternmost point of the Trans-Canada Highway and joins continental Canada via ferry, while a highway to northern Quebec joins Labrador to the rest of the country. Prince Edward Island is linked to New Brunswick via the Confederation Bridge. Completed in 1997, the 12.9 km stretch is the longest bridge in the world over seasonally ice-covered water (Strait Crossing Bridge Ltd., 2015) and facilitates the movement of people and goods between the mainland and the island year-round. The Trans-Canada Highway connects New Brunswick to Quebec and areas west through the most northwestern point of the province, and to Nova Scotia across the Chignecto Isthmus). Trucking accounts for about $500 million in trade flow annually across the Isthmus (Webster et al., 2012; Marlin, 2013).

Figure 5: Atlantic Canada's road network.



3.2 MARINE TRANSPORTATION

Each Atlantic province has specialized marine transportation infrastructure. The Port of Halifax is the most significant marine hub in Nova Scotia and the third-largest container port in Canada. Its deep, ice-free harbour provides services for both international and short-sea shipping, and contributed $1.6 billion to the Atlantic economy in 2013 (Port of Halifax, 2015; Cirtwill et al., 2001). The Port also features significant intermodal infrastructure, transferring goods to railcars and trucks bound for the U.S. Northeast and Midwest, Quebec, and Ontario (Canada's Atlantic Gateway, 2010). It recently completed a $35 million expansion to host wider, post-Panamax[6] containerships (Power, 2012).

The Ports of Saint John in New Brunswick and Placentia Bay in Newfoundland also move significant volumes of freight, and handle more crude oil and refined petroleum products than Halifax (Canada's Atlantic Gateway, 2010). These products make up the majority of Atlantic Canada's marine freight, much of which originates in Newfoundland. Ferries also play an important role in moving freight (as well as people). Marine Atlantic, a crown corporation providing ferry services, accounts for approximately 50 percent of all goods shipped to and from Canada's mainland to Newfoundland via Port aux Basques and/or Argentia to North Sydney crossings (Marine Atlantic, 2015).

Marine tourism is another important contributor to the region's economy, operating at peak capacity in summer. The cruise industry is growing in Atlantic Canada, accounting for 31 percent of Canada's total marine passenger traffic in 2012 (Cruise Lines International Association, 2013; Transport Canada, 2014). The Charlottetown Harbour Authority reports an increase in cruise ship passenger traffic of approximately 400% between the years 2007 and 2015 (Corryn Morrissey, Charlottetown Harbour

6 Post-Panamax describes ships that do not fall within the current allowable dimensions for passing through the Panama Canal. Operators of the Panama Canal are currently constructing a new lock system, designed to handle these larger "post-Panamax" ships.

Authority, personal communication, 2016). Ferry routes support tourism and regional connectivity. In Newfoundland and Labrador, a number of ferry routes travel from Labrador to the island of Newfoundland, including St. Barbe-Blanc Sablon and Goose Bay-Cartwright-Lewisporte. Ferries from North Sydney, Nova Scotia travel to Newfoundland, while Nova Scotia connects to Prince Edward Island via the Caribou-Wood Island Ferry. Other key routes include the Nova Scotia-New Brunswick route via Digby to Saint John, and the route operating between Prince Edward Island and Îles de la Madeleine, Quebec (Souris to Cap-aux-Meules) (Ferry CTMA, 2015).

3.3 AIR TRANSPORTATION

Atlantic Canada's airports move over 7.8 million people annually, a figure more than three times the region's population size (Atlantic Canada Airports Association, 2012). The airport system includes seven National Airports System (NAS)[7] airports (below) in addition to many smaller community airports:

- Fredericton International Airport, Greater Moncton International Airport, and Saint John Airport (New Brunswick);
- Gander International Airport, and St. John's International Airport (Newfoundland and Labrador);
- Halifax Stanfield International Airport (Nova Scotia); and
- Charlottetown Airport (Prince Edward Island).

Less freight is moved by air than by other modes in the Atlantic region – usually only time-sensitive or specialty goods. However, freight volumes are still significant, with over 60,000 metric tonnes moved annually (Atlantic Canada Airports Association, 2012).

4.0 ROAD TRANSPORTATION: IMPACTS AND ADAPTATIONS

4.1 PAST IMPACTS AND FUTURE RISKS

A number of climate-related variables, including extreme weather events, storm surges, and freeze-thaw cycles, have impacts on both road infrastructure and operations in Atlantic Canada.

EXTREME EVENTS

The most severe regional-scale impacts are related to tropical or post-tropical storms, and associated with heavy precipitation, strong winds, and storm surges. Examples include Hurricane Juan (September 2003), which resulted in $100 million in direct damages to infrastructure in Halifax alone, including roads and highways (Bowyer, 2003a), and Hurricanes Earl and Igor, which struck within a week of each other in September, 2010 resulting in road closures throughout Atlantic Canada. In Newfoundland and Labrador, approximately 150 communities were isolated by road closures during Hurricane Igor, and parts of the Trans-Canada Highway were washed away (Canadian Climate Forum, 2014). The prospect of more frequent extreme weather events (i.e. shortened return periods) will increase the risk of roadway flooding which strands users, increases driving times, disrupts freight flows, and can disrupt emergency services (Chu, 2012; Vasseur and Catto, 2008).

Wind gusts from 80-160 km/h have been recorded regionally during tropical and post-tropical storm events (Environment Canada, 2013b). High winds have closed major Atlantic bridges such as Halifax's MacDonald Bridge and the Confederation Bridge (Catto et al., 2006). In summer 2014, Hurricane

[7] The NAS designation is given to airports in provincial capitals and other airports with annual traffic exceeding 200,000 passenger movements (Transport Canada, 2010).

Arthur uprooted hundreds of trees in Fredericton, New Brunswick, blocking streets until city crews could remove the fallen vegetation (Case Study 1).

High winds also occur independently of tropical storms. For instance, 170 km of highway (from Moncton, New Brunswick to Truro, Nova Scotia) through the Chignecto Isthmus has been closed due to strong winds and blowing snow (CBC News, 2015a). Also, the stretch of Trans-Canada Highway near Wreckhouse, Newfoundland and Labrador often experiences strong winds funnelled from the southern end of the Long Range Mountains. Trucking companies in this region use constant-monitoring technology to reduce accident risks. One Newfoundland company has reported trucks overturning due to high winds in Wreckhouse and the Northern Peninsula (Fleming, 2014).

CASE STUDY 1

CASE STUDY 1: HURRICANE ARTHUR'S IMPACTS ON TRANSPORTATION IN FREDERICTON

Fredericton, New Brunswick (population 57,000) is located on a broad sweep of the Saint John River. Flooding, from spring freshets and heavy rain events has historically been difficult for Fredericton to manage.

On Saturday July 5, 2014, Hurricane Arthur transformed into a strong post-tropical storm and made landfall in western Nova Scotia. Fredericton experienced a prolonged period of heavy rain and high winds from the storm system, including 150 mm of rain (recorded at Base Gagetown near Fredericton) and 100 km/h wind gusts at Fredericton International Airport. The combination of wind and rain saturated the soil and caused widespread tree damage and power outages in the city.

The storm affected roads and sidewalks, the public walking trail network, and Fredericton International Airport. City crews struggled to remove trees that had fallen across roadways and trails, disrupting traffic. In many cases, electrical lines were intertwined with branches, requiring a joint response from New Brunswick Power and the City to clear routes for emergency vehicles. The airport also experienced a lengthy power outage and relied on generators to maintain operations.

Hurricane Arthur was not typical in that it was an early-season tropical storm, hitting Fredericton when trees were at their heaviest due to the weight of new leaf growth (and before branches and trunks had strengthened to support this growth). More intense and unusual weather events, such as Arthur, have the City rethinking standard business practices, including:

- Planting different tree species and varieties in public rights- of-way to ensure resilience and minimize tree failure, which will reduce impacts to the street, trail, and sidewalk system;
- Implementing an intensive pruning program to enable trees to withstand severe weather; and
- Reviewing and upgrading staff training and equipment in anticipation of future storms.

The City is also working jointly with the University of New Brunswick Forestry program to undertake a street-tree inventory. Prior to replanting trees, characteristics such as height, root system, canopy, and resilience of various species will be assessed to ensure that new trees can better withstand high winds and soil saturation.

This example illustrates the indirect impacts of extreme weather on transportation operations, particularly in urban environments. Collaboration across sectors such as electricity, forestry, and transportation is important to enhance the resilience of urban systems to climate change.

Written by Ken Forest (Growth and Community Services, City of Fredericton, New Brunswick).

Storm surges can cause coastal erosion and flooding, affecting roadways close to shore (Province of Nova Scotia, 2009b). The structural integrity of one major bridge in Corner Brook, Newfoundland, has nearly been compromised on multiple occasions by storm surges. City officials have been forced to close the bridge at times for safety (Rayna Luther, City of Corner Brook Infrastructure and Public Works, personal communication, 2015). The segment of Trans-Canada highway in the Chignecto Isthmus is also sensitive to storm-surge inundation (see Case Study 5).

In Prince Edward Island, where no point is more than 16 km from the sea, infrastructure is especially vulnerable to high-water damage. For example, a severe storm surge in December 2010 resulted in several bridge closures and significant washouts at various locations including Oyster Bed Bridge, Corran Ban Bridge and Rustico Bridge (Figure 6). Additionally, the predominantly sandstone composition of Prince Edward Island's coastline is inherently susceptible to erosion resulting from storm surge and high water events. In Prince Edward Island, at least two coastal public roads have been abandoned in recent years, due to erosion (Brian Thompson, Government of Prince Edward Island, personal communication, 2016). This results not only in disruptions to property owners, and the traveling public, but in unscheduled government expenditures to secure land and construct alternate routes where applicable (Brian Thompson, Government of Prince Edward Island, personal communication, 2016). Coastline erosion rates have been increasing in P.E.I. The average rate of erosion grew from 28 cm per year between 1968 and 2010, to 40 cm per year between 2000 and 2010 (Webster, 2012). Without taking into account rising sea levels and increasing storms associated with climate change, an assessment of coastal infrastructure in the province identified over 40 kilometres of roads at risk from coastal erosion by 2100 (Fenech, 2014).

The frequency and magnitude of storm-surge flooding will increase over the 21st century in areas that experience sea-level rise, including most of Atlantic Canada. This in turn increases risks to coastal roads and bridges.

Figure 6: Flooding of Oyster Bed Bridge during a storm in December, 2010. (Source: Don Jardine)

TEMPERATURE AND PRECIPITATION CHANGES

Freeze-thaw cycles are taxing on road systems, particularly when temperature changes are rapid. When the frequency of freeze-thaw cycles increases, the potential for rapid road deterioration and higher maintenance costs rises as well. For example, by the end of approximately three weeks of fluctuating winter conditions in February 2015, Halifax had over 1,000 outstanding potholes – approximately 300 were more than two inches deep and therefore assigned a "priority" designation (Bradshaw, 2015). These cycles are expected to become more frequent throughout most of the Atlantic region over the short term. Freeze-thaw frequency is expected to decline over the long term as average winter temperatures rise (Boyle et al., 2013).

Rain-on-snow events also affect Atlantic Canada's roads. In 1962, approximately 180 mm of rain on heavy snow on Prince Edward Island's southern coast caused extensive washouts and damage to paved highways (Atlantic Climate Adaptation Solutions Association, 2011). A similar event in December 2014 caused $9 million in damages to bridges and roadways in Prince Edward Island (McCarthy, 2014; Wright, 2015). Rapid snow melt can also cause problems for municipal drainage systems. When temperatures ranged from -27°C to 7°C in the span of a month in Corner Brook, Newfoundland, mass snow-thaws resulted in the infiltration of large water volumes in short periods of time, overloading the capacity of stormwater management infrastructure (Rayna Luther, City of Corner Brook Infrastructure and Public Works, personal communication, 2015).

Warmer winters are associated with more frequent freezing rain and black-ice conditions, affecting traffic flow, accident rates, maintenance costs, and the use of anti-icing chemicals (Andrey et al., 2013). Warmer winter temperatures also affect the safety and usability of informal seasonal ice routes in northern Labrador and New Brunswick that provide access to and from communities across frozen bodies of water (CBC News, 2012; Nalcor Energy, 2014).

Extreme temperatures also have negative effects on road infrastructure. Interior regions of New Brunswick and Nova Scotia have already experienced an increase in the frequency of hot days, and this trend is expected to continue (Steeves, 2013), increasing the risk of road damage and adding stress to bridge joints. While extreme cold is not likely to increase in frequency, abnormally cold days will continue to occur (Gao et al., 2015), reducing the fuel-efficiency of vehicles and contributing to icy conditions.

4.2 ADAPTATION PRACTICES

In light of these impacts, governments and private operators are using a number of strategies to enhance the resilience of road infrastructure. Flood risks are a particular focus of these efforts.

PHYSICAL PROTECTION MEASURES

Some Atlantic municipalities are constructing seawalls, breakwaters, and dykes to protect roads against sea-level rise and higher storm surges (Liverman et al., 1994; Batterson et al., 1999; Halifax Regional Municipality, 2012). These buffers protect low-lying infrastructure from overtopping (which occurs when water rises higher than a dyke or levee). The construction of higher dykes and breakwaters may mediate the impacts of unpredictable flows of water in parts of Atlantic Canada (Graham and Musselman, n.d.). Case Study 2 discusses an example of this type of adaptation in Halifax, Nova Scotia.

In areas of extreme concern, such as the Chignecto Isthmus corridor, "hardening" of the surrounding land by means of a dyke system has protected the roads to date, although further efforts (hard, soft and hybrid engineering approaches) to protect infrastructure and communities under projected climate scenarios have recently been investigated (see Case Study 5).

CASE STUDY 2

CASE STUDY 2: DEFENSIVE ADAPTATION IN COW BAY (HALIFAX, NOVA SCOTIA)

The Cow Bay Causeway is a 350 m stretch of road built over a beach of cobble and boulder. For many years, despite protection by a breakwater, the road was susceptible to damage from wave overwash. Three specific problems were identified with the existing breakwater:

1. The breakwater was not high enough in some areas to prevent waves from overtopping.
2. Most of the existing armour stone was not of sufficient size to resist the force of waves during a major storm; the causeway was closed at least twice a year for safety reasons.
3. Voids between the existing armour stones allowed small stones and seaweed to wash through the breakwater and be deposited on the roadway.

As a result, the causeway often experienced extensive damage from storms, and required repairs every three to five years. The severity and impacts of recent storms (including Hurricane Juan in 2003, post-tropical storm Noel in 2007, and a January 2010 storm) and risks of future impacts prompted the Halifax Regional Municipality to commission a study and recommendations for the redesign of the causeway and its breakwater. The study employed a statistical risk assessment model known as the Coastal Infrastructure Adaptation Planning System (CIAPS) to analyze the interaction of future tidal and storm-surge conditions along the coast with the anticipated performance of the existing breakwater, as well as to determine the appropriate elevations for more resilient infrastructure (Davies et al., 2010). Four adaptation alternatives were identified:

1. Erosion-proofing the causeway by replacing gravel shoulders with articulated concrete mats;
2. Erosion-proofing, plus elevating the roadway to minimize overtopping risks;
3. Rebuilding the barrier in its entirety (including impermeable technologies); or
4. Rebuilding the barrier in prioritized phases (Davies et al., 2010).

Figure 7: Cow Bay Causeway experiencing a storm. (Photo of Cow Bay Causeway taken January 26th, 2010 by M. Davies, Coldwater Consulting Ltd)

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The risk assessment suggested that the cost-optimized solution was to rebuild the causeway's breakwater in two phases. The design included:

- An increase in the height of the breakwater;
- A 600 mm-by-2.5 m concrete core;
- 4-to-8-tonne armour stone on the outer face of the breakwater;
- A breakwater crest approximately 9 m wide; and
- A seaward slope (two blocks horizontal for one block vertical).

Each phase included completion of approximately half of the breakwater length, and the design allowed for the increase in wave height anticipated under future sea-level and storm-surge conditions. The project was tendered in 2012, and Phase 1 was awarded with a budgeted construction cost of $670,000 (Davies et al., 2010; Halifax Regional Municipality, 2012). Phase 2 was completed in 2013.

While the new breakwater has not yet dealt with a major hurricane event, local practitioners suggest that the infrastructure has been successful in mitigating the effects of heavy storms and wave action to date (David Hubley, Halifax Regional Municipality, personal communication, 2016).

Written by Eric Rapaport with input from David Hubley (Halifax Regional Municipality).

STORMWATER MANAGEMENT PRACTICES

Throughout Atlantic Canada, cities are reducing risks to roadways from flood events by improving stormwater management practices. These include:

- using future climate projections to update design flows in stormwater management networks to account for increased precipitation. Examples include the City of Fredericton, New Brunswick (Arisz, n.d.), the City of Corner Brook, Newfoundland (City of Corner Brook, 2012), and the Town of Stratford, Prince Edward Island (CBCL Ltd., 2012).
- using the Public Infrastructure Engineering Vulnerability Committee's (PIEVC) risk assessment protocol to assess the climate change vulnerability of roads and stormwater management systems. Examples include Sandy Point, Nova Scotia; Miramichi, New Brunswick; and, Placentia, Newfoundland and Labrador (Municipality of the District of Shelburne, 2011; City of Miramichi, 2013; Engineers Canada, 2014). In response to PIEVC recommendations, Sandy Point is investing in new pumping stations to reduce infiltration and flows onto infrastructure, and both Miramichi and Placentia are considering larger culvert sizes along the road corridors that were assessed (City of Miramichi, 2013; Engineers Canada, 2014).

Additional stormwater management practices identified in the literature may also be relevant to Atlantic Canada. These include building rain gardens/retention ponds; using permeable pavement materials; planting trees (to increase infiltration and reduce water pooling on roads), and coordinating stormwater management at the watershed-scale (i.e. maintaining natural river channels and wetlands) (Marsalek and Schreier, 2010; Kessler, 2011).

INFRASTRUCTURE RELOCATION

Relocating or flood-proofing road infrastructure may be required, where the shoreline is at risk of being inundated or unusable, due to sea-level rise, storm surges, and coastal erosion (Transportation Research Board, 2008; Davidson-Arnott and Ollerhead, 2011). Some municipalities in Atlantic Canada have chosen to locate new roads away from coastal areas (Graham and Musselman, n.d.); or elevate infrastructure when feasible (i.e. Moncton, New Brunswick; see Chapter 9) (AMEC Inc., 2011). For example:

- The Confederation Bridge, which connects PEI to the Canadian mainland in New Brunswick, was built to accommodate a one metre rise in sea levels over 100 years. The bridge was also designed to allow ice blocks to pass safely underneath (Gregg, 2010).
- The Prince Edward Island Department of Transportation is rebuilding the Souris bridge one metre higher, due to sea level rise projections (Government of Prince Edward Island, 2015).
- Nova Scotia's provincial government recently rebuilt its 100-series highways further inland from their original coastal locations to provide safer and faster corridors; as a result, these highways are much less sensitive to coastal hazards (Finck, 2013).
- The New Brunswick Department of Transportation rebuilt and raised a bridge on the main road into Pointe-du-Chêne to accommodate future sea-level rise (Daigle, 2011).
- Relocation of the section of Trans-Canada Highway along the Chignecto Isthmus has been discussed as a potential long-term adaptation solution, but is presently considered too costly (see Case Study 5).

OPERATIONAL AND MAINTENANCE PRACTICES

Operators are also adapting to challenging weather conditions. For example, one trucking company in Newfoundland, experiencing more frequent repairs due to difficult road and weather conditions, has found a creative way to ensure business continuity (Fleming, 2014). Towing trucks to the company's facility in Corner Brook is expensive and time consuming; therefore, the company now strategically leaves replacement parts in customers' homes and businesses along its routes (Fleming, 2014). When minor repairs are required (i.e. tires, springs, and lights), drivers contact the closest facility to request delivery or replacement of the appropriate parts. The company's connections to local communities make this approach possible.

Governments are investing in proactive maintenance to reduce climate risks to transportation infrastructure. For instance, to reduce spring flood risks in rural New Brunswick resulting from periods of rapid warming and snowmelt, the federal government invested $1.7 million in 2015 to proactively remove snow from the roadways of eight vulnerable First Nations communities. As many as 800 truckloads of snow per day were removed from critical infrastructure (including roadways) in some communities. Regional snowfall in winter 2014 broke local records and contained higher-than-normal water content, making snow difficult for communities to remove (Water Canada, 2015; Aboriginal and Northern Development Canada, 2015).

5.0 RAIL TRANSPORTATION: IMPACTS AND ADAPTATIONS

5.1 PAST IMPACTS AND FUTURE RISKS

Rail infrastructure in Atlantic Canada is affected by a changing climate and extreme weather in many of the same ways as roads. For example, flooding (caused by extreme precipitation, storm surge, and ice jams) has resulted in impacts on both modes (Environment Canada, 2010), and snowstorms that inundated roadways in St. John’s, Newfoundland in 1959 and Prince Edward Island in 1989 also buried and stranded trains (Environment Canada (2013b).

STORM SURGE, COASTAL EROSION, AND SEA-LEVEL RISE

Coastal rail lines in Atlantic Canada are vulnerable to flooding, washouts, and damage associated with storm surge and erosion, which can sometimes result in derailments. For example, in 2003 Hurricane Juan resulted in 1.5-2 m storm surges at Halifax Harbour that severely eroded shoreline, washed-out railway tracks (Figure 8), and washed several rail cars into the ocean at the Dartmouth rail yard (Bowyer, 2003a). Similarly, Hurricane Igor in 2010 caused rail-line damage, washout, and closures – these were especially pronounced in Newfoundland (Curtis and Ehrenfeld, 2012).

Figure 8: Debris on rail track at Dartmouth Point the morning after Hurricane Juan. Run-up was 1.64 m above the highest water level recorded at the Halifax tide gauge across the harbor, and water levels remained unusually high at the time of photography. (Source: Natural Resources Canada)

In 1974, a wind storm accompanied by high seas washed-out 30 m of railway track and derailed two diesel trains at Cape Ray, Newfoundland (Heritage Newfoundland and Labrador, n.d.). Coastal erosion has resulted in damaged tracks, slower speeds, operational delays, and rail closures in Atlantic Canada, affecting the movement of goods such as paper, coal, lumber, petroleum products, and chemicals (Genesee and Wyoming, Inc., n.d.). These disruptions have negative impacts on local industries (including intermodal facilities) due to delayed shipping, production, and refinement, and foregone profits/revenues.

Slope failures in coastal areas have affected the Quebec North Shore and Labrador Railway (QNS & L) (Batterson et al., 1999; CBC News, 2014b), and will continue to pose risks in future (Spooner et al., 2013; Evan et al., 2005). Similarly, the Cape Jack section of the Cape Breton and Central Nova Scotia Railway (CBNS) has experienced severe erosion around coastal sections of track (Stephen Newson, Province of Nova Scotia, personal communication, 2015; CBC News, 2014a).

Looking forward, an area of considerable concern is the Chignecto Isthmus, which is vulnerable to flooding and where flood risks will increase significantly throughout the 21 century as a result of sea-level rise (Webster et al., 2011) (Figure 9; see Case Study 5).

Figure 9: CN Rail in the Chignecto Isthmus. Embankments form part of the region’s dyke network. (Source: EOS Eco-Energy Inc.)

EXTREME PRECIPITATION

There are many documented incidents of heavy precipitation events affecting rail transport in Atlantic Canada. For example, on August 31, 2007, heavy rain caused a number of culverts to fail along CBNS rail in Cape Breton, Nova Scotia, as well as wash-outs along many sections. The track was closed for approximately three weeks for repair and replacement, disrupting freight movement (Stephen Newson, Province of Nova Scotia, personal communication, 2015). In total, the incident cost the railway more than $500,000 (Province of Nova Scotia, 2007a, 2007b).

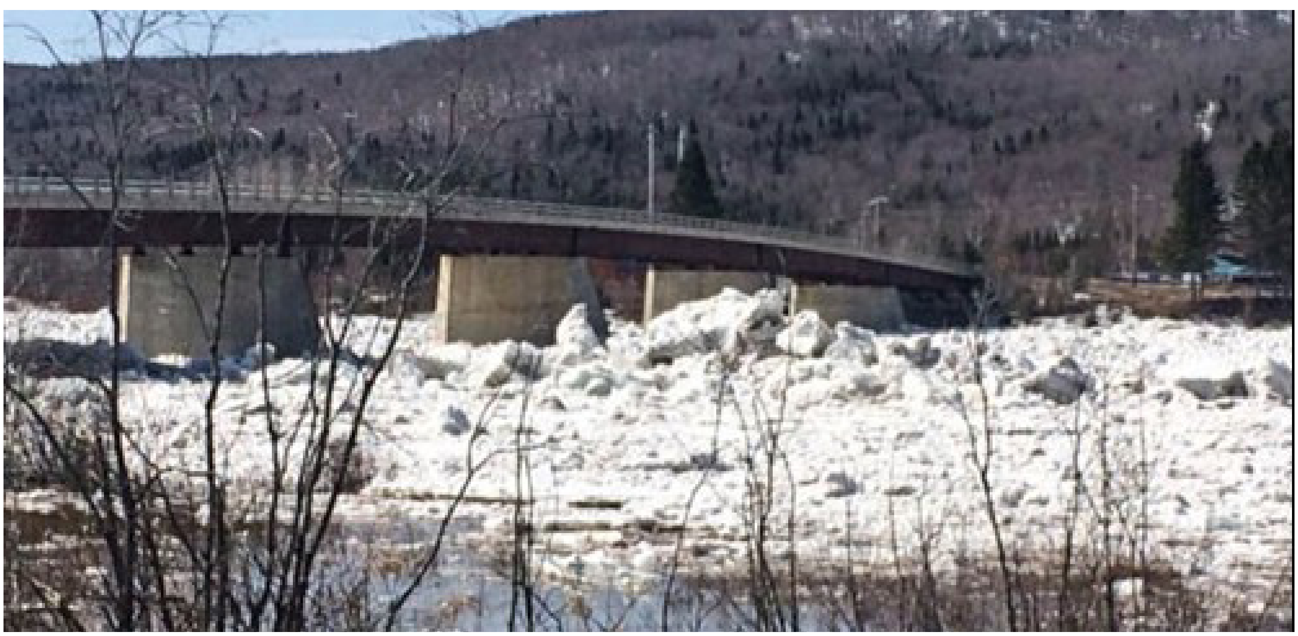
In April 2003, culverts beneath a rail line in Ellershouse, Nova Scotia washed out during a large storm event (Stephen Newson, Province of Nova Scotia, personal communication, 2015). Similarly a severe tropical storm in December 2010 caused significant damage to rail infrastructure near Fredericton, New Brunswick, as extreme precipitation washed-out rail bridges and undermined rail beds (Environment Canada, 2013c). Future increases in the intensity, duration, and frequency of extreme precipitation (Bush et al., 2014) would result in even more severe impacts.

Heavy snow also disrupts rail movements in Atlantic Canada. For instance, snowstorms in Nova Scotia during winter 2015 delayed the movement of goods and services by rail from multimodal facilities to North American markets, proving costly for operators (Henderson, 2015; Cuthbertson, 2015). Heavy snow will continue to affect rail movements in Atlantic Canada, at least over the short term.

ICE-JAM FLOODING

Inland flooding associated with snowmelt and ice jams[8] have caused major damage to rail systems. Floods involving ice jams tend to be more damaging to infrastructure than open-water events, particularly to bridges. For example, during a February 1970 flood on the Saint John River, New Brunswick, a series of ice jams on six rivers resulted in the destruction of 32 bridges (both road and rail) and damage to 124 others (see Figure 10) (Government of New Brunswick, 2012).

Figure 10: Spring ice jam at a rail bridge on the Saint John River. (Source: New Brunswick Power, 2015)



[8] An ice jam is a temporary ice blockage of a river, formed by the accumulation of ice fragments that build up to restrict the flow of water. Ice jams form during both the freeze-up and breakup periods, but it is usually breakup jams that have the greater flooding potential. Over two thirds of total provincial flood damage costs in the Saint John River basin are due to ice-related events (Environment Canada, 2013a).

In April 1987, an ice jam caused the collapse of the Perth-Andover railway bridge, during a severe spring flooding event in New Brunswick. Loaded rail cars had been placed on the bridge to hold back the ice jam and prevent flooding downstream, a practice that had been successfully employed during a less-severe spring flood event in 1976; however in 1987, the pressure of the ice and floodwaters caused the bridge to fail (Environment Canada, 2010). In future, the likelihood of ice-jam flooding may increase as the timing of seasonal change becomes more variable from year to year (Government of New Brunswick, 2014).

TEMPERATURE

Increasing average air temperatures and changing extremes pose uncertain risks to rail transportation in Atlantic Canada. Hot and cold temperature extremes cause rail tracks to expand or contract, and can lead to train derailments (Dobney et al., 2008; Peterson et al., 2008; Nova Scotia Department of Transportation and Infrastructure Renewal, 2014). Extreme summer heat can result in rails buckling as they expand beyond reasonable design limits (Dobney et al., 2008), causing "sun kinks". Historically this has not been a common problem in the Atlantic provinces (Stephen Newson, Province of Nova Scotia, personal communication, 2015). However, the region has experienced incidents caused by, or exacerbated by, rapid temperature changes. For example, the investigation into a derailment in Pictou County, Nova Scotia in June 2014 indicated that track buckling "produced by a sudden and unusual fluctuation of rail temperature and accumulated steel stress" was a significant contributor (Province of Nova Scotia, 2014). Extreme temperature change is also considered to have been a major factor in a main-track derailment in Milford, Nova Scotia in 2002 (Transportation Safety Board of Canada, 2003). The frequency of these events – and the probability of a serious accident – is likely to increase as temperatures rise in the 21st century (Dobney et al., 2008).

5.2 ADAPTATION PRACTICES

While documented examples are limited, rail operators in Atlantic Canada have made efforts to reduce future climate risks. For example, an emergency culvert and aboiteaux[9] system in Hantsport, Nova Scotia was constructed to accommodate increased water flow through culvert systems under rail tracks (Figure 11). The overflow openings allow excess water during extreme precipitation or flooding situations to drain from the culvert via an alternate route. This prevents culvert blowouts during periods of heavy flow (Stephen Newson, Province of Nova Scotia, personal communication, 2015).

Figure 11: Overflow aboiteaux at Hantsport, Nova Scotia. (Source: Danika Van Proosdij)

[9] This refers to a series of protective dykes around low-lying farmland to prevent tidal inundation (Hatvany, 2002).

In the past, the general solution to erosion under rail lines was to replace fallen or sunken rock. However, due to the increasing frequency of repairs and associated costs, this method may no longer be sufficient or effective (Stephen Newson, Province of Nova Scotia, personal communication, 2015). Physical barriers, such as dykes have also been used to protect rail infrastructure from the effects of storm-surge flooding, and erosion, but these protections may not be sufficient in future. Adaptation options are currently being examined for dyke systems in the Chignecto Isthmus, for example (Case Study 5).

One practice that has been used to increase the resilience of rail infrastructure vulnerable to temperature extremes is to replace continuously welded rail (CWR) with shorter segments, which have joints allowing track to expand and contract (Lim et al., 2003). (CWR, which has longer rail segments, generally reduces track maintenance costs and increases the average service life of rail components under moderate temperature conditions). For example, following the June 2014 derailment in Pictou, 300 feet of CWR from the point of derailment was replaced with 39-foot track panels that are easier to maintain and replace in the event of stress caused by heat or temperature fluctuations. Additionally, the company conducted a stress test on the rail line, and employees reviewed rail maintenance requirements. To prevent similar events in the future, the railway has developed a new technical training program, and train speeds have been restricted to 40 km/h during summer months and may be further restricted to as low as 16 km/h when warranted by extreme heat conditions (Province of Nova Scotia, 2014).

6.0 MARINE TRANSPORTATION

6.1 PAST IMPACTS AND FUTURE RISKS

Marine transportation in Atlantic Canada has long been affected by adverse climate conditions and storms, disrupting operations and damaging vessels, ports, and navigation infrastructure. These impacts are particularly challenging for Newfoundland and Labrador, which relies heavily on marine transportation for resupply and connectivity (CBC News, 2015b, 2015c). Over the past century, improved forecasting and monitoring technologies have considerably reduced risks to marine operators from extreme weather. However, ports and vessels remain vulnerable to a number of future risks associated with a changing climate. Lost productivity from weather-related disruptions in Atlantic Canada's marine transportation sector is estimated to total millions of dollars annually (Catto et al., 2006).

PRECIPITATION, EXTREME WEATHER, STORM SURGE, AND SEA-LEVEL RISE

Hurricanes have caused major damage to marine infrastructure and vessels in the past. During Hurricane Juan, storm surges of 1.5-2 m and wind gusts up to 230 km/h, damaged coastal wharves and other port infrastructure in Halifax Harbour, blew containers off ships, snapped weather buoys, and sank and damaged vessels (Bowyer, 2003a Bowyer, 2003b). "White Juan", a hurricane-force nor'easter in February 2004 (five months after the hurricane), resulted in 10-15 m waves and a storm surge that further damaged ports in Nova Scotia (Environment Canada, 2013a). In 1995, during Hurricane Luis, a 30 m wave struck an ocean liner off the coast of Newfoundland (Environment Canada, 2013b).

Rising sea levels and increased storm surge are also expected to pose greater risks over the course of the 21st century (Bush et al., 2014). Sea-level rise in the range of 70-100 cm is projected for many key coastal locations in Atlantic Canada by 2100 (Savard et al., 2016); and in some cases, higher tides and storm surges could inundate and damage wharves, terminals, and loading equipment in the absence of adaptive action (Andrey and Mills, 2003). Figures 12a and 12b illustrate the extent of possible inundation for Halifax Harbour in 2100, based on two sea-level rise scenarios (high- and low-probability). In some locations sea-level rise could permit the entry of ships with greater drafts and heavier cargo loads (Andrey and Mills, 2003).

Figure 12a: Flooding extent/depth in Halifax Harbour associated with a 10-year return level event and a 0.57 m rise in global sea level (highly plausible). For these projections, it is assumed that frequency and intensity of storms remains unchanged in future. (Source: Forbes et al., 2009)

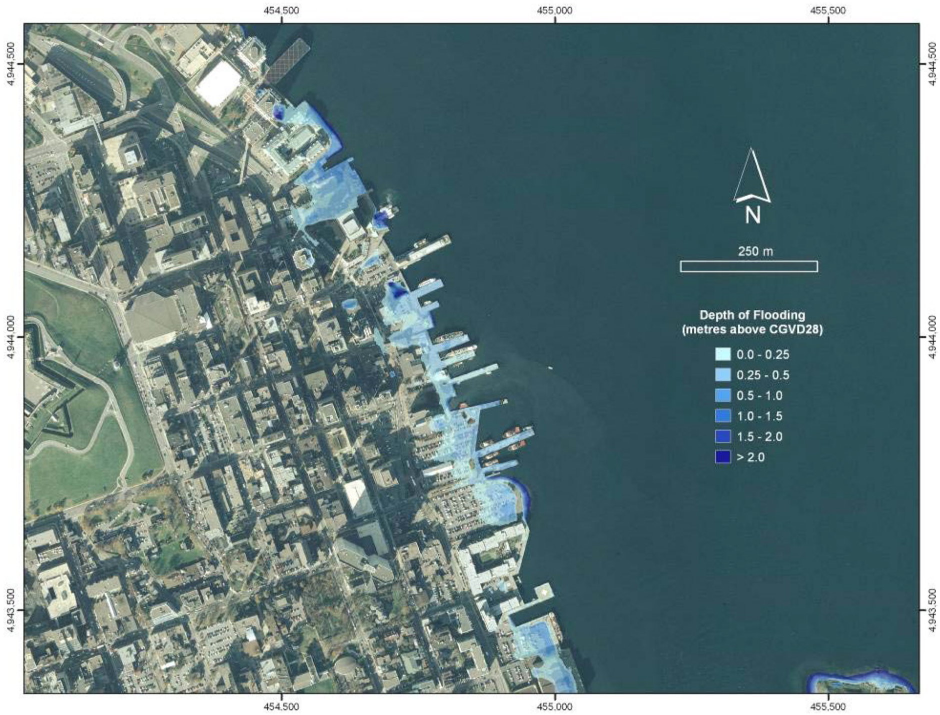
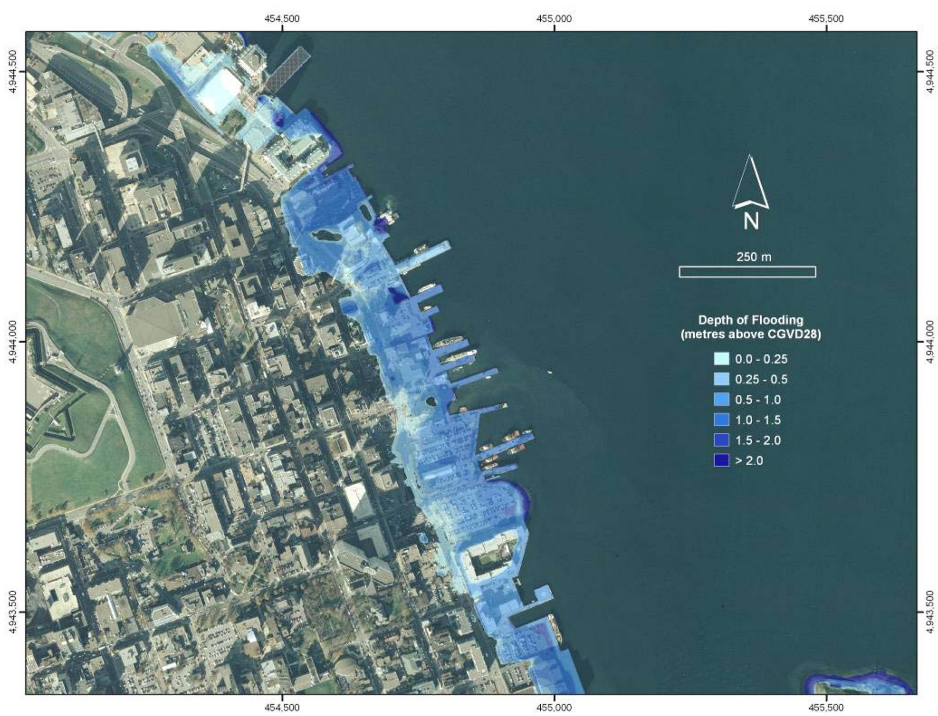


Figure 12b: Flooding extent/depth in Halifax Harbour associated with a 50-year return level event and a 1.3 m rise in global sea level (lower probability). For these projections, it is assumed that frequency and intensity of storms remains unchanged in future. (Source: Forbes et al., 2009)



SEA ICE AND WIND

High winds have been a source of costly delays for ferries servicing Newfoundland, Labrador, and Nova Scotia (CBC News, 2015b; Cape Breton Post, 2015; Catto et al., 2006). When combined with earlier seasonal break-up and fragmentation of sea ice, winds pose additional navigation hazards. For instance, in the winter of 2015, ice blown into the Strait of Belle Isle resulted in lengthy delays and frustration for passengers attempting to travel between Newfoundland and Labrador (CBC News, 2015b). Similarly, increasing easterly wind strength in Channel-Port aux Basques, Newfoundland may threaten the reliability of ferry transportation in the area, an important crossing point from the island to the mainland (Catto et al., 2006).

High winds will continue to pose risks to vessels and ports, based on projected increases to the frequency of extreme weather events. At the same time, warmer summer weather and the decreasing extent and duration of sea ice will offer potential benefits to commercial shipping, the cruise industry, and eco-tourism via an extended Maritime shipping season (Andrey and Mills, 2003; Leys, 2009; Savard et al., 2016).

CASE STUDY 3

CASE STUDY 3: PLANNING FOR FUTURE EXTREME WEATHER CONDITIONS AT HALIFAX HARBOUR

The Province of Nova Scotia, with support from Natural Resources Canada has been conducting a case study on the impacts of climate change on coastal transportation infrastructure in Halifax Harbour. Researchers are using cost-benefit analysis to assess vulnerabilities to changing climate parameters and adaptation options. Analysis focuses on marine shipping and intermodal transfers to truck and rail. This includes an investigation of how rail delays resulting from extreme weather or infrastructure damage might affect the delivery of goods to marine ports. The results of this study were not yet available at the time of writing this assessment.

Variables under consideration in the study included sea-level rise, storm surge, and coastal subsidence. Maps and computer models were used to visualize potential impacts on the system. Volunteer participants in the study included CN rail and major port operators. This cost-benefit analysis will help to demonstrate the impacts of climate change on businesses near Halifax Harbour.

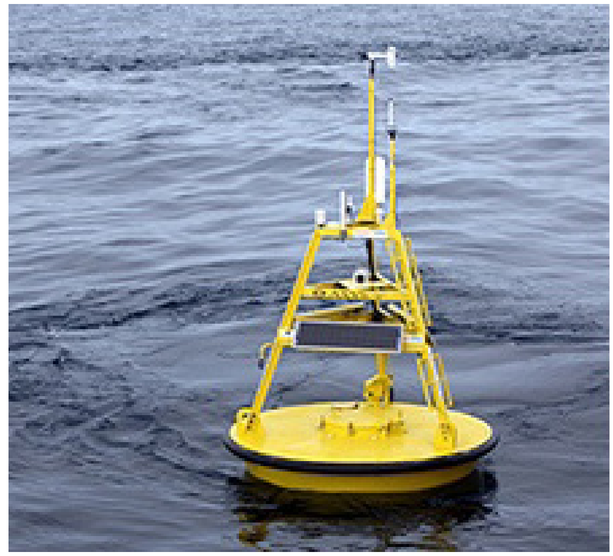
Written with input from Shawn MacDonald (Climate Change Unit, Government of Nova Scotia).

6.2 ADAPTATION PRACTICES

Atlantic Canada's marine ports and operators have employed a number of practices to improve their resilience to climate and extreme weather risks. One example is Bay Bulls Harbour (Figure 13), an economic hub in eastern Newfoundland that is proximate to St. John's and the productive fishing grounds of the Grand Banks. In 2010, Hurricane Igor caused extensive damage to the wharf. When the wharf was reconstructed, the community elected to include adaptive measures to better withstand future storm conditions. Sea-level rise, storm surges, and extreme weather were considered. As a result, the new wharf was built 0.5 m higher than previously, its directional orientation was changed, and a breakwater of 1.5 m was constructed to provide increased protection. Bay Bulls and its economic assets are now better-prepared for higher-intensity weather conditions (Office of Climate Change, Energy Efficiency and Emissions Trading, 2013). There are an increasing number of cost/benefit analyses demonstrating that capital and other expenditures undertaken to reduce risks of infrastructure damage result in long-term cost savings (see Case Study 5).

Figure 13: Bay Bulls Harbour, Newfoundland. (Source: Government of Newfoundland and Labrador Office of Climate Change and Energy Efficiency)

Figure 14: SmartAtlantic buoy in St. John's, Newfoundland. (Source: Fisheries and Marine Institute of Memorial University)



An under-explored area of adaptation is the application of new technologies to reduce climate risk. For example, the Fisheries and Marine Institute of Memorial University of Newfoundland and the Institute for Ocean Research Enterprise of Halifax have created the SmartAtlantic Alliance to further modernize Canada's marine navigation system by providing accurate and real-time meteorological and hydrological data. Data generated by SmartAtlantic buoys (Figure 14) is used to produce high-resolution forecasts of weather and sea conditions, and for scientific research. The technology is currently in use at seven Atlantic ports (see Case Study 4) and allows the marine transportation industry, commercial and recreational boaters, researchers, and interested members of the public to access real-time, online data about regarding weather and directional wave information at these locations. It is designed to optimize efficiency without compromising navigational safety, and to enhance the reliability of port operations in a variety of weather and climatic conditions (Government of Canada, 2014; New Brunswick Department of Transportation and Infrastructure, 2015).

CASE STUDY 4

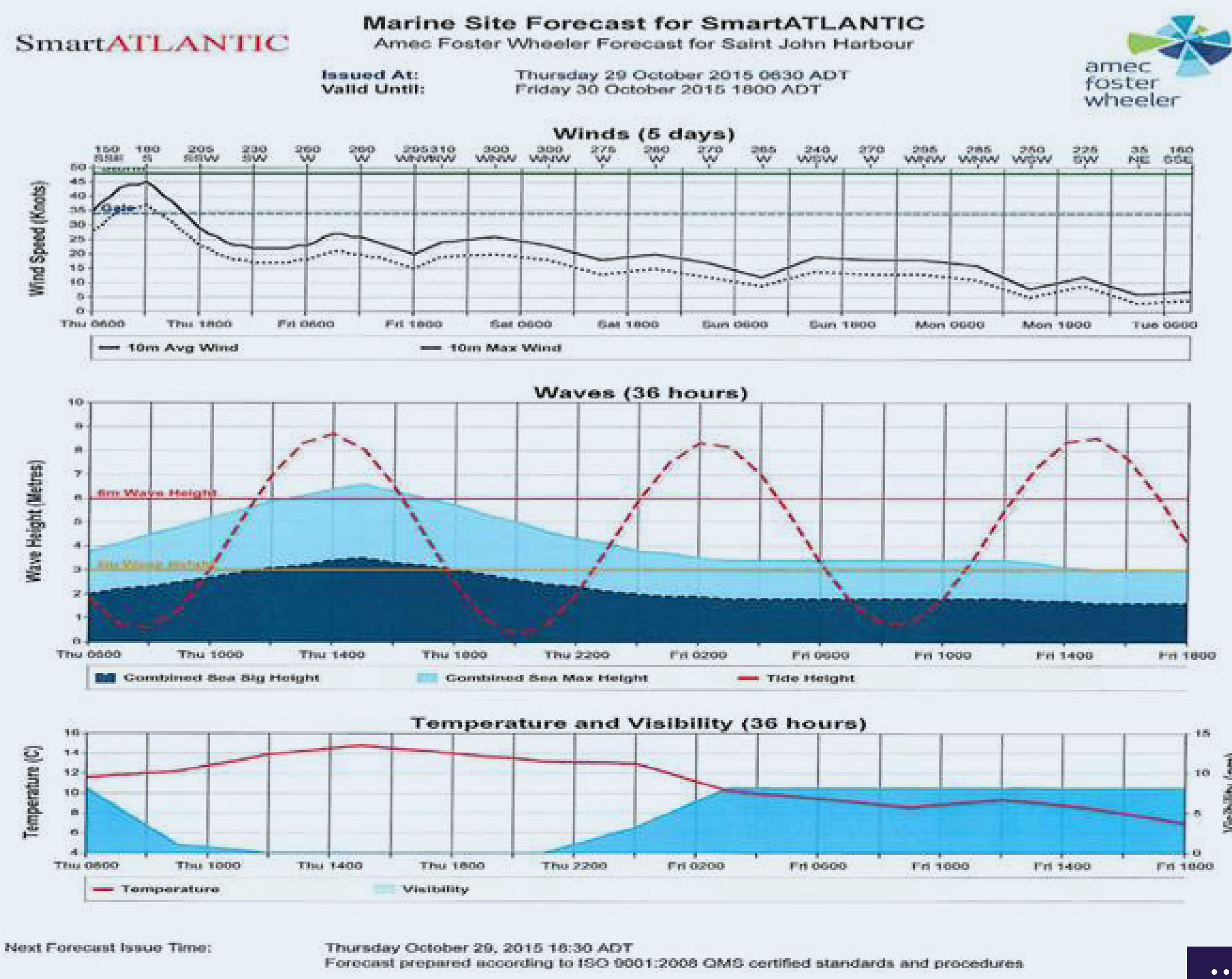
CASE STUDY 4: CLIMATE CHANGE ADAPTATION AT PORT SAINT JOHN

Port Saint John is Atlantic Canada's largest port by tonnage. It connects global markets to central Canada by rail and road, and serves regionally-important industries such as potash, petroleum, and tourism (i.e. the cruise industry). Climate-related impacts and disruptions to the port's operations negatively affect the regional and national economy, as well as the Port's profitability. Port operators have identified a number of risks to infrastructure and operations related to extreme, variable and/or changing climatic conditions. Spring flooding has been particularly problematic.

Sea-level rise and storm surges pose increasing risks to port infrastructure, designed for a 100-year lifespan. In late 2015-early 2016, Port Saint John experienced an unusually high number of strong wind events, producing storm surges in the inner harbour. During one particularly strong event on October 29, 2015 (the peak of which coincided with an extra high tide), infrastructure sustained approximately $20,000 in damages (Chris Hall, Port Saint John, personal communication, 2016).

Several actions, implemented and planned by the Port as part of its modernization efforts, are expected to make the port more resilient to variable and changing climatic conditions, and more reliable for shippers and mariners. For example, the "SmartAtlantic" inshore weather buoy was recently launched, along with a wave forecasting tool. Figure 15 provides an example of the forecasting output from Saint John Harbour's SmartAtlantic buoy. This data accurately predicted the storm-surge event on October 29, 2015.

Figure 15: SmartAtlantic buoy output for Saint John Harbour (October 29, 2015). (Source: Chris Hall, Port Saint John)



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The Port is also undertaking long-term planning for its infrastructure as part of a port modernization plan. A preliminary engineering study in support of these efforts explicitly accounted for future sea level rise, based on high-resolution models for the Upper Bay of Fundy (Dupont et al., 2005).

Written with input from Chris Hall (Port Saint John) with additional information provided by Tyler O'Rourke (Port Saint John).

7.0 AIR TRANSPORTATION

7.1 PAST IMPACTS AND FUTURE RISKS

Practitioners suggest that on the whole, airports in the Atlantic region are well-equipped to function during difficult weather conditions. However, extreme weather events and storms, including heavy rain, snowfall, and strong winds, can result in flight delays and cancellations, associated economic losses, and passenger inconvenience. Flight delays are especially problematic for Newfoundland (CBC News, 2015b, 2015c), which relies on aviation (as well marine transportation) for connectivity.

Airports aim to keep facilities open in all weather conditions, especially for medical emergency services that require the use of runways and airport facilities. The challenge for airports is to provide efficiency of service while ensuring safe operations during extreme weather conditions. Atlantic airports are particularly concerned with rising operating costs accompanying more variable and severe weather conditions (Helen MacInnis, J.A. Douglas McCurdy Sydney Airport, personal communication, 2015; Andrew Isbill, Fredericton Airport Authority, personal communication, 2015).

PRECIPITATION AND STORMS

Precipitation, including rain, snow, and freezing rain on runways can compromise the friction and visibility necessary for planes to take off and land. Operational costs can also rise significantly in response to freezing rain events and extreme snowfall (Helen MacInnis, J.A. Douglas McCurdy Sydney Airport, personal communication, 2015).

Increasingly frequent storm events (and associated precipitation and flooding) in the 21st century could lead to further losses in revenue due to operational disruptions. These types of delays could also increase operating costs, associated with requirements for more aircraft, facility maintenance and the improvement of supporting infrastructure, such as access roads and drainage facilities (Transportation Research Board, 2008).

While storm surges, erosion and sea-level rise pose risks to regional coastal infrastructure, most airports in Atlantic Canada are built on relatively high ground, which reduces vulnerability to coastal flooding.

Drainage systems are usually effective in reducing flood risks to runways. However, extreme precipitation events have, in some instances, flooded airport service/access roads and parking lots in Atlantic Canada. In some cases, these floods have delayed and cancelled flights, as was the case at Halifax Stanfield International Airport during a strong nor'easter in December 2014 (CBC News, 2014c).

Increased frequency of lightning storms and hurricanes are also a concern for some airports in Atlantic Canada, given their potential to disrupt operations and pose safety risks (for instance, by reducing visibility during landing and take-off). While data to support the increasing frequency of these storms are not captured in the historical record, Sydney airport has documented an increase in frequency over the short term (Helen MacInnis, J.A. Douglas McCurdy Sydney Airport, personal communication, 2015).

WIND

High winds can result in cancelled, delayed or redirected flights when cross winds are too strong for aircraft to safely take off or land (United Kingdom Department for Transport, 2014). Wind can also damage equipment on the ground. For instance, in 2012, high winds tipped over an array (part of the instrument landing system) at the J.A. Douglas McCurdy Sydney Airport in Nova Scotia, affecting landing operations and requiring NAV CANADA to make unexpected and costly repairs (Helen MacInnis, J.A. Douglas McCurdy Sydney Airport, personal communication, 2015).

Power outages accompanying windstorms can create major problems for air transportation. For example, when Hurricane Arthur hit the Maritimes in the summer of 2014, Fredericton International Airport lost power and had to rely on a backup generator (Andrew Isbill, Fredericton Airport Authority, personal communication, 2015). The generator allowed the airport to continue with some operations, although operators had concerns about its potential failure. More frequent high-intensity wind events would increase risks associated with these impacts, although projections indicate that daily average wind speeds are not likely to increase significantly in the Atlantic region (Loder et al., 2013).

TEMPERATURE

Atlantic aviation is also vulnerable to changing temperatures. Increasing freeze-thaw cycles pose risks to runway stability, while extreme heat and cold reduce aircraft engine performance and fuel efficiency (Transportation Research Board, 2008).

Increasing turbulence as a result of higher-temperature conditions (increased air density) is expected to affect flights in the North Atlantic by mid-century. The proportion of flight time for transatlantic journeys spent in conditions of "moderate-or-greater turbulence" is likely to increase 40-170 percent by mid-century, resulting in longer trip times, greater fuel consumption, and more greenhouse-gas emissions (Williams and Joshi, 2013).

7.2 ADAPTATION PRACTICES

Adaptation actions at Atlantic airports are not well documented in the public domain. However, Atlantic aviation faces many of the same climate risks as operators in other Canadian jurisdictions (including extreme weather events and temperature extremes). Thus, many of the practices outlined in other chapters of this report apply to Atlantic Canada. General risk avoidance practices include standard procedures for accessing weather forecasts and planning flights, and for advanced aircraft instrumentation systems.

8.0 MULTI-MODAL RISK ASSESSMENTS AND COST-BENEFIT ANALYSES

Some initiatives in Atlantic Canada have considered the vulnerability of the region's transportation network with a multimodal lens. These include risk assessments and cost-benefit analyses of climate change impacts and adaptation options for transportation infrastructure.

8.1 RISK ASSESSMENTS

In 2012, the Department of Fisheries and Oceans (DFO) completed an expert-based risk assessment of infrastructure, waterways, and biological systems in the Atlantic Large Aquatic Basin (LAB), which includes the Newfoundland Labrador Shelf, Scotian Shelf/Slope, and the Gulf of Maine (Department of Fisheries and Oceans, 2013). The assessment process identified and rated six key risks based on "risk exposure" (vulnerability to impacts) on 10- and 50-year horizons. Risks relevant to transportation include increased demand for emergency services, infrastructure damage, and changes to the navigability of waterways. Of these, it was determined that the greatest risks are posed to infrastructure by changing climate conditions over both timescales. Authors note that this assessment's methodology can be applied to smaller-scale risk assessments of ports and coastal transportation systems in Atlantic Canada.

Public and private institutions are developing tools to assist in the assessment of climate change risks. For example, the "CoastaL Impact Visualization Environment" (CLIVE) tool, created in partnership by the University of Prince Edward Island (UPEI) and Simon Fraser University, offers a "virtual tour" of likely coastal erosion and storm-surge impacts on Prince Edward Island. CLIVE is operated by a game controller and allows the user to "fly" over Prince Edward Island's coastline, examining past and future sea levels (at 30, 60, and 90 year future intervals). This tool also quantifies sea-level rise risks, including land area lost. This tool is useful for assessing transportation infrastructure vulnerability to coastal changes in order to better plan for changes in maintenance, structure, or location over the short and long term (Office of the Vice-President, Research, 2015).

8.2 COST-BENEFIT ANALYSIS

Some practitioners in the region are undertaking cost-benefit analyses of adaptation options in order to ensure the benefits of a given option outweighs the costs associated with climate change. The costs of direct (damages) and indirect (disruptions and closures) climate impacts on transportation systems can be significant. At the same time, adaptation efforts can be costly – infrastructure is expensive to build, and changing operational practices can cause short-term delays, confusion, and other inefficiencies (Füssel, 2007). Case Study 5 summarizes a cost-benefit analysis of climate impacts and adaptation options for the Chignecto Isthmus.

CASE STUDY 5

CASE STUDY 5: ADAPTING TO FLOODING AND STORM-SURGE RISKS IN THE CHIGNECTO ISTHMUS

The Chignecto Isthmus is one of Canada's most important transportation corridors, and the sole land bridge joining mainland Canada (New Brunswick) with Nova Scotia. Marsh areas within the Isthmus had dykes installed in the 1700s for agriculture. Since that time, significant infrastructure has been built within this area, including the Trans-Canada Highway, the CN Railway, and electricity-transmission lines serving Nova Scotia. Trade through the Isthmus is conducted by both road and rail, carrying an estimated value of $50 million per day and $20 billion annually.

Recent studies demonstrate the vulnerability of the region to sea-level rise and storm-surge flooding (Webster et al., 2011, Lieske and Bornemann, 2012; and Webster et al., 2012). By 2100, 38 km of dykes, 19 km of rail, and 19 km of the Trans-Canada Highway could be severely affected by flooding in a 1-in-100 year storm event (Figure 16). However, there has been a lack of information on the economic costs associated with these impacts in the Chignecto region.

A collaborative cost-benefit analysis (CBA) of adaptation options (including maintaining the status quo) was undertaken to assess the economic consequences of sea-level rise and storm surge on significant infrastructure (highways, rail, agricultural dykes, and electricity) and trade in the Isthmus. The project features collaboration among the Provinces of New Brunswick and Nova Scotia and Natural Resources Canada. The CBA had three objectives:

- Build on existing local assessments of climate change impacts and adaptation options, adding economic analysis to the discussion.
- Quantify economic costs associated with flood-related damages to the transportation corridor in order to demonstrate the benefits (monetary and otherwise) associated with potential adaptation options.
- Support decision-makers in the selection of informed adaptation investments.

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Six adaptation options were assessed (see Table 3). These options mainly focus on changes that could be made to the management of agricultural dykes in the Isthmus, which currently protect farmland against tidal flooding, and provide secondary protection for roads, rail, and infrastructure. However, the dykes are not designed to withstand severe storm events. Summaries of adaptation options are presented below. A key assumption in the study was that no option could result in increased risks or damages to the communities and municipal infrastructure of Sackville and Amherst.

Figure 16: 100-year flood event (in blue) for the Chignecto Isthmus in 2070 in relation to road, rail, and electrical transmission infrastructure. (Source: MacDonald and Webster, Applied Geomatics Research Group)

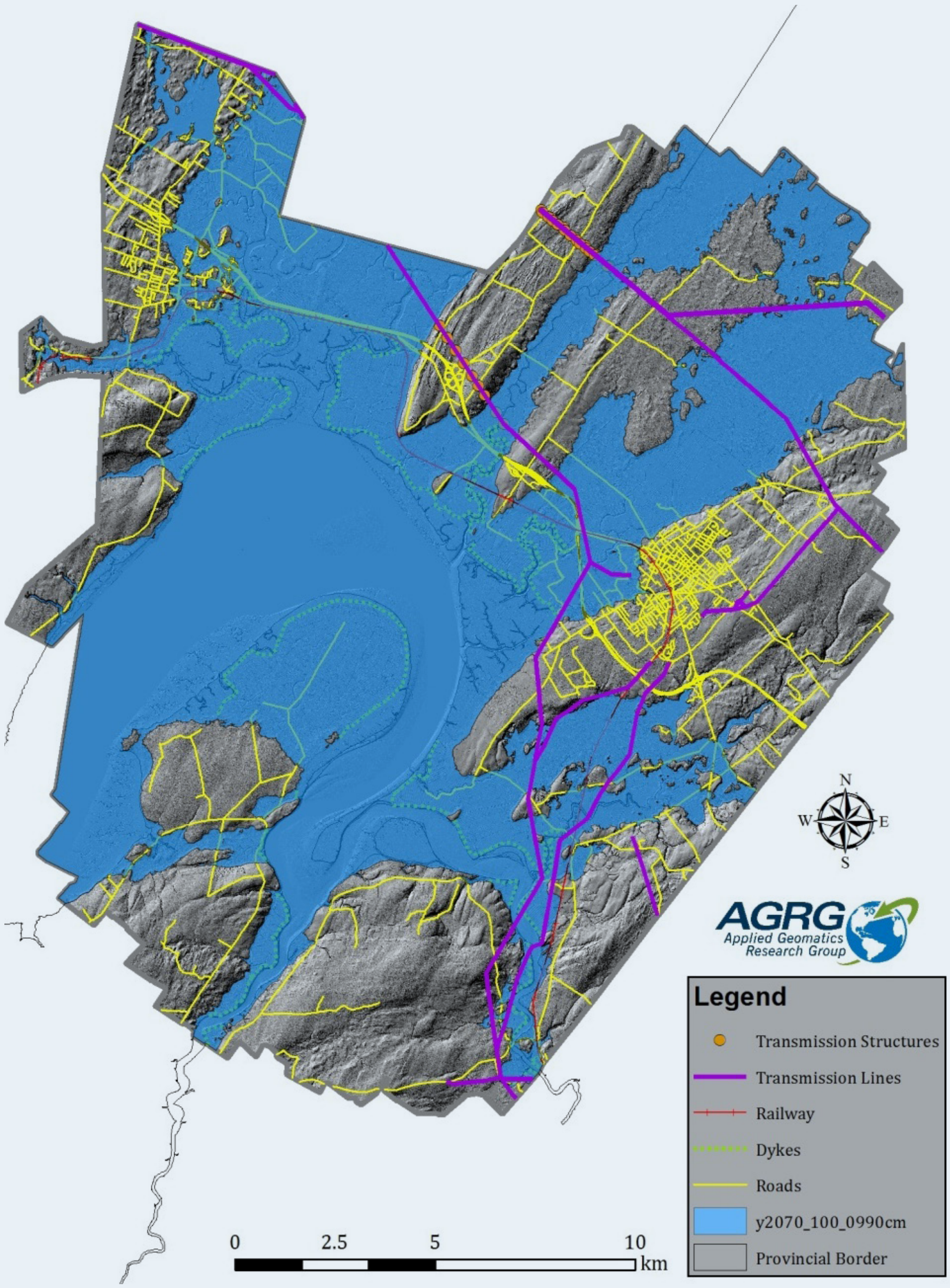

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Table 3: Adaptation options evaluated in the Chignecto Isthmus CBA.

Option Number	Adaptation Option	Description
1	Agricultural dykes, existing location	Raising/topping-up dykes in existing locations to 10 m. Public infrastructure not protected behind dykes.
2	Agricultural dykes, shortened	Combination: Topping-up dykes and rebuilding to 10 m in existing locations, but shortened in certain sections. Raise infrastructure.
3	Engineered dykes, existing location	Build engineered dykes on top of existing dykes, engineered to 2070, 1-in-100-year events (10 m).
4	Engineered dykes, shortened, protect public infrastructure only	Shorten dykes, build engineered dykes on top of existing dykes, as well as new stretches, engineered to 2070, 1-in-100-year events (10 m); raise rail that is not being protected by existing dykes.
5	Engineered dykes, shortened protect all infrastructure	Shorten dykes, build engineered dykes on top of existing dykes, as well as new stretches, engineered to 2070, 1-in-100-year events (10 m).
6	Re-route the Trans-Canada Highway (50km)	Re-route a vulnerable 50 km stretch of the Trans-Canada Highway.

RESULTS

The CBA is a high-level analysis intended to provide strategic direction on adaptation options – not to inform operational-level decision-making or costing.

The cost of impacts associated with climate change over the period from 2015 to 2064 in today's dollars is estimated at $124 million. When potential trade loss is incorporated, this cost rises to $435 million.

The preferred adaptation option is an approach involving engineered dykes designed to protect against flooding associated with a 1-in-100 year storm event in 2070 (Option 3). Dykes would be shortened (compared to their current length) and protect all infrastructure (road, rail and electricity). The cost of the preferred option is estimated at approximately $93 million and its Net Present Value – calculated as the difference between the benefits of adaptation and costs of climate change impacts (discounted for evaluation in dollars today at 4 percent) – is estimated at $31 million. When lost trade due to climate change impacts is broadly accounted for, the Net Present Value of the preferred option grows to $278 million.

In this case, the cost of taking no adaptation action exceeds the costs associated with infrastructure renewal.

Lessons learned from the project relate to the challenges of integrating divergent stakeholder interests – however, practitioners believe the project has allowed for information-sharing around a common threat. Given that agricultural and transportation departments have typically worked separately, the process is likely to provide a more coordinated approach to the future management of the Isthmus. This study highlights the value of the dykes, and has challenged all stakeholders to think collaboratively and critically about how assets are protected in the Chignecto region.

Written with input from Jeff Hoyt (Government of New Brunswick) and Sabine Dietz (Aster Group Environmental Services).

9.0 INFORMATION GAPS AND CONCLUSIONS

Several gaps and barriers related to climate change adaptation in Atlantic Canada's transportation sector are evident. First, there is an absence of vulnerability assessments and comprehensive data specific to transportation in the Atlantic region. While risk assessment protocols have been applied to identify climate vulnerabilities in some cases, it is not known which specific roads, rail, airports and ports are most and least vulnerable. In addition, for certain important weather conditions such as fog and wind, there is little relevant, published climate data and literature from which to draw conclusions. Wind and fog have major impacts on marine and air navigation in the Atlantic region, so further research could better inform planning and operations.

The research conducted for this chapter also suggests that the risks to assets and operations posed by extreme weather events are more salient to public and private infrastructure managers than those related to long-term changes in climate parameters (i.e. sea-level rise, increased ambient temperatures). Greater attention is given by municipalities, practitioners, and infrastructure operators (i.e. Halifax Harbour, Port Saint John) to the increasing frequency of extreme weather events over other, longer-term impacts. This is not surprising, given limited public resources and the high costs incurred by flooding and other catastrophic events.

Likely for this same reason, practitioners and researchers conducting risk assessments and adaptation planning in Atlantic Canada acknowledge challenges in engaging stakeholders. The relevance of climate change to business owners can be difficult to explain – sea-level rise is a long-term process that does not fit neatly into conventional business cycles.

Despite some of these difficulties, this chapter has identified a number of tangible adaptation efforts in the transportation sector, just one sector among many in Atlantic Canada considering how to adapt to emerging climate risks (Atlantic Climate Adaptation Solutions Association, 2016). Climate change adaptation is a growing issue on the transportation agenda, and climate risks are spurring investment and planning. Practitioners are aware that the demand for transportation services will change in response to physical damages and service disruptions caused by changing climate conditions, and actions taken to enhance economic access to new or expanded markets will alter the supply and demand of freight in the region. Ensuring an efficient and resilient transportation infrastructure through collaboration and adaptation will be important to reduce impacts and maximize benefits from a changing climate.

10.0 ANNEX

Tables A1-A4: Temperature and precipitation projections by province for the Atlantic region up to 2100 over three time horizons (2016-2035, 2046-2065, and 2081-2100). Seasonal periods include winter (December-February), spring (March-May), summer (June-August), and autumn (September-November). Data was derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate model under an ensemble of RCP2.6, RCP4.5, and RCP8.5 scenarios (Canadian Climate Data and Scenarios, 2015). These data reflect uncertainty associated with these projections by presenting a range of values from the 25th-75th percentiles of CMIP5 outputs. The median value (50th percentile) appears in brackets following the range.

Table A1: Temperature and precipitation projections for New Brunswick.

Climate scenario (Representative Concentration Pathway)	Climate variable	Season	Projected change from 1986-2005 baseline (25th- 75th percentiles; 50th percentile in brackets)		
			Near term 2016-2035	Mid-century 2046-2065	Late-century 2081-2100
RCP 2.6 (Low-emissions scenario)	Precipitation (%)	Winter	+1.1-10.1 (+4.8)	+1.0-12.4 (+6.7)	+0.9-9.9 (+3.5)
		Spring	+1.4-8.5 (+5.4)	+2.1-10.2 (+5.9)	+2.2-10.5 (+7.3)
		Summer	-3.4-+5.8 (+2.8)	-2.7-8.6 (+1.1)	-0.6-10.1 (+3.9)
		Autumn	-1.9-+4.6 (+1.9)	-2.7-+4.2 (+0.6)	-2.8-+6.1 (+2.7)
	Temperature (˚C)	Winter	+0.8-1.4 (+1.1)	+1.3-2.3 (+1.7)	+1.4-2.7 (+2.1)
		Spring	+0.6-1.2 (+0.9)	+0.8-2.0 (+1.6)	+0.7-2.0 (+1.2)
		Summer	+0.8-1.4 (+1.0)	+1.0-2.1 (+1.5)	+0.8-1.8 (+1.4)
		Autumn	+0.9-1.4 (+1.0)	+1.2-2.3 (+1.6)	+1.0-2.0 (+1.5)
RCP 4.5 (Intermediate-emissions scenario)	Precipitation (%)	Winter	-0.7- +10.1 (+5.2)	+3.6-15.2 (+8.9)	+7.0-19.1 (+11.9)
		Spring	-0.6-+8.8 (+4.1)	+3.9-13.2 (+10.1)	+6.1-19.1 (+12.5)
		Summer	-2.2-+8.2 (+3.0)	+0.2-9.1 (+3.9)	-0.7-+11.3 (+4.5)
		Autumn	-2.5-+5.9 (+1.1)	-0.8-+9.5 (+5.9)	-3.1-+6.7 (+1.4)
	Temperature (˚C)	Winter	+0.7-1.8 (+1.3)	+2.0-3.3 (+2.7)	+2.9-4.3 (+3.5)
		Spring	+0.6-1.5 (+1.0)	+1.4-2.5 (+1.8)	+1.8-3.2 (+2.7)
		Summer	+0.7-1.4 (+1.1)	+1.5-2.6 (+2.1)	+2.0-3.5 (+2.5)
		Autumn	+0.9-1.5 (+1.1)	+1.7-2.6 (+2.1)	+2.2-3.6 (+2.5)

Climate scenario (Representative Concentration Pathway)	Climate variable	Season	Projected change from 1986-2005 baseline (25th- 75th percentiles; 50th percentile in brackets)		
			Near term	Mid-century	Late-century
			2016-2035	2046-2065	2081-2100
RCP 8.5 (High-emissions scenario)	Precipitation (%)	Winter	-0.2-+11.3 (+5.8)	+6.0-17.3 (+11.4)	+13.1-28.6 (+19.0)
		Spring	+0.1-7.3 (+3.4)	+6.1-15.1 (+10.6)	+12.0-23.0 (+16.6)
		Summer	-2.3-+6.6 (+3.2)	-1.3-+9.9 (+4.2)	-1.1-+14.8 (+7.8)
		Autumn	-4.2-+3.7 (-0.4)	-1.0-+10.4 (+3.5)	+1.2-10.3 (+4.3)
	Temperature (˚C)	Winter	+1.0-1.9 (+1.4)	+3.0-4.4 (+3.6)	+5.6-7.3 (+6.4)
		Spring	+0.8-1.5 (+1.0)	+2.2-3.5 (+2.7)	+4.2-6.0 (+4.6)
		Summer	+1.0-1.6 (+1.2)	+2.4-3.7 (+3.0)	+4.4-6.3 (+5.4)
		Autumn	+1.0-1.8 (+1.3)	+2.5-3.8 (+3.1)	+4.4-6.2 (+5.1)

Table A2: Temperature and precipitation projections for Newfoundland and Labrador.

Climate scenario (Representative Concentration Pathway)	Climate variable	Season	Projected change from 1986-2005 baseline (25th- 75th percentiles; 50th percentile in brackets)		
			Near term	Mid-century	Late-century
			2016-2035	2046-2065	2081-2100
RCP 2.6 (Low-emissions scenario)	Precipitation (%)	Winter	-2.4-+8.1 (+3.2)	-0.1-+11.8 (+5.8)	+1.0-12.9 (+6.3)
		Spring	+1.2-10.2 (+5.3)	+1.7-13.3 (+8.1)	+2.7-13.3 (+7.9)
		Summer	-0.2-+7.3 (+3.5)	+0.8-9.8 (+4.8)	+0.3-8.8 (+4.3)
		Autumn	+0.7-8.1 (+4.3)	+1.1-9.0 (+5.3)	+1.9-9.8 (+6.0)
	Temperature (˚C)	Winter	+0.8-1.8 (+1.3)	+1.4-3.0 (+2.2)	+1.3-3.3 (+2.3)
		Spring	+0.4-1.2 (+0.8)	+0.7-1.9 (+1.2)	+0.5-1.9 (+1.1)
		Summer	+0.5-1.2 (+0.8)	+0.7-1.8 (+1.2)	+0.6-1.7 (+1.2)
		Autumn	+0.7-1.3 (+1.0)	+1.0-2.1 (+1.6)	+0.9-2.1 (+1.5)

Climate scenario (Representative Concentration Pathway)	Climate variable	Season	Projected change from 1986-2005 baseline (25th- 75th percentiles; 50th percentile in brackets)		
			Near term	**Mid-century**	**Late-century**
			2016-2035	**2046-2065**	**2081-2100**
RCP 4.5 (Intermediate-emissions scenario)	Precipitation (%)	Winter	-0.3-+11.7 (+5.0)	+2.9-16.1 (+9.5)	+6.5-20.8 (+14.5)
		Spring	+0.7-11.5 (+6.0)	+3.8-13.7 (+8.5)	+5.1-17.4 (+10.5)
		Summer	-0.6-+7.8 (+3.3)	+0.7-10.7 (+5.1)	+2.2-10.5 (+5.9)
		Autumn	-0.6-+7.2 (+3.2)	+3.3-10.2 (+7.2)	+2.7-10.7 (+7.1)
	Temperature (˚C)	Winter	+0.8-2.0 (+1.3)	+2.2-3.7 (+2.9)	+2.9-4.9 (+4.1)
		Spring	+0.4-1.2 (+0.8)	+1.1-2.3 (+1.6)	+1.6-2.8 (+2.1)
		Summer	+0.5-1.3 (+0.8)	+1.2-2.3 (+1.7)	+1.5-3.0 (+2.2)
		Autumn	+0.8-1.3 (+1.0)	+1.5-2.5 (+1.8)	+1.9-3.3 (+2.3)
RCP 8.5 (High-emissions scenario)	Precipitation (%)	Winter	+0.6-10.6 (+4.8)	+6.5-20.7 (+12.0)	+14.2-34.8 (+23.0)
		Spring	+0.8-9.0 (+5.4)	+5.6-15.8 (+10.2)	+12.0-28.5 (+18.9)
		Summer	-1.7-+7.9 (+3.5)	+2.2-11.2 (+6.6)	+5.3-18.6 (+11.5)
		Autumn	+0.2-7.2 (+3.8)	+4.0-11.5 (+7.8)	+7.2-18.9 (+12.2)
	Temperature (˚C)	Winter	+1.0-2.2 (+1.5)	+3.4-5.2 (+4.3)	+6.5-9.0 (+7.7)
		Spring	+0.5-1.4 (+1.0)	+2.0-3.1 (+2.4)	+3.8-6.0 (+4.7)
		Summer	+0.8-1.3 (+1.0)	+1.9-3.2 (+2.5)	+3.9-5.9 (+4.6)
		Autumn	+0.9-1.5 (+1.2)	+2.3-3.5 (+2.7)	+4.2-6.2 (+4.8)

Table A3: Temperature and precipitation projections for Nova Scotia.

Climate scenario (Representative Concentration Pathway)	Climate variable	Season	Projected change from 1986-2005 baseline (25th- 75th percentiles; 50th percentile in brackets)		
			Near term 2016-2035	Mid-century 2046-2065	Late-century 2081-2100
RCP 2.6 (Low-emissions scenario)	Precipitation (%)	Winter	-0.1-6.2 (+2.8)	-2.2-+7.0 (+2.5)	+0.3-7,8 (+3.0)
		Spring	+1.7-8.0 (+4.0)	+0.9-10.1 (+3.6)	+1.9-9.8 (+6.6)
		Summer	-3.9-+7.3 (+2.8)	-3.8-+8.0 (+2.2)	-2.9-+9.2 (+2.6)
		Autumn	-1.8-+4.2 (+1.5)	-2.7-+5.0 (+1.7)	-2.1-+6.5 (+2.2)
	Temperature (˚C)	Winter	+0.7-1.3 (+1.0)	+1.1-2.1 (+1.5)	+1.0-2.5 (+1.9)
		Spring	+0.6-1.2 (+0.9)	+0.8-1.9 (+1.4)	+0.7-1.9 (+1.3)
		Summer	+0.7-1.2 (+0.9)	+1.0-1.8 (+1.5)	+0.9-1.8 (+1.3)
		Autumn	+0.8-1.3 (+1.0)	+1.1-2.1 (+1.5)	+1.0-1.8 (+1.4)
RCP 4.5 (Intermediate-emissions scenario)	Precipitation (%)	Winter	-1.8-+6.1 (+2.8)	+2.9-9.3 (+5.4)	+4.1-14.4 (+8.7)
		Spring	-0.8-+7.6 (+3.5)	+2.8-13.7 (+8.1)	+4.0-16.5 (+8.6)
		Summer	-2.2-7.6 (+3.0)	-3.6-9.2 (+4.4)	-1.3-9.8 (+6.4)
		Autumn	-0.9-+6.3 (+2.7)	-1.3-+9.1 (+4.8)	-3.7-+9.1 (+3.8)
	Temperature (˚C)	Winter	+0.7-1.6 (+1.2)	+1.7-2.9 (+2.3)	+2.4-3.7 (+2.9)
		Spring	+0.6-1.4 (+1.0)	+1.5-2.2 (+1.7)	+1.8-2.9 (+2.5)
		Summer	+0.7-1.5 (+1.0)	+1.5-2.4 (+1.9)	+1.9-3.2 (+2.4)
		Autumn	+0.8-1.4 (+1.1)	+1.6-2.5 (+1.9)	+2.1-3.5 (+2.4)

Climate scenario (Representative Concentration Pathway)	Climate variable	Season	Projected change from 1986-2005 baseline (25th- 75th percentiles; 50th percentile in brackets)		
			Near term	Mid-century	Late-century
			2016-2035	2046-2065	2081-2100
RCP 8.5 (High-emissions scenario)	Precipitation (%)	Winter	+0.6-6.7 (+3.7)	+6.5-12.5 (+8.3)	+14.2-21.1 (+13.9)
		Spring	+0.5-8.6 (+4.4)	+3.8-13.8 (+7.6)	+7.3-18.1 (+12.8)
		Summer	-4.5-+5.8 (+1.7)	-2.2-+8.5 (+4.3)	-3.0-+15.3 (+6.8)
		Autumn	-4.6-+4.0 (-0.3)	-1.8-+8.8 (+4.0)	-0.6-8.6 (+3.7)
	Temperature (˚C)	Winter	+.9-1.6 (+1.3)	+2.5-3.6 (+3.0)	+4.7-6.2 (+5.4)
		Spring	+0.7-1.4 (+1.0)	+2.1-3.2 (+2.5)	+3.9-5.5 (+4.4)
		Summer	+0.9-1.5 (+1.1)	+2.2-3.4 (+2.7)	+4.1-6.6 (+4.9)
		Autumn	+0.9-1.6 (+1.2)	+2.3-3.6 (+3.0)	+4.2-6.0 (+4.8)

Table A4: Temperature and precipitation projections for Prince Edward Island.

Climate scenario (Representative Concentration Pathway)	Climate variable	Season	Projected change from 1986-2005 baseline (25th- 75th percentiles; 50th percentile in brackets)		
			Near term	Mid-century	Late-century
			2016-2035	2046-2065	2081-2100
RCP 2.6 (Low-emissions scenario)	Precipitation (%)	Winter	+1.2-8.7 (+3.0)	-2.3-8.8 (+5.2)	+2.1-8.0 (+5.3)
		Spring	+1.3-7.8 (+5.6)	+1.1-9.8 (+6.2)	+4.1-9.8 (+7.7)
		Summer	-3.7-+8.1 (+0.6)	-4.3-+7.7 (+1.9)	-1.4-+6.6 (+2.7)
		Autumn	-3.3-+4.0 (+1.6)	-5.2-+5.5 (+0.9)	-3.3-+5.5 (+2.8)
	Temperature (˚C)	Winter	+0.8-1.6 (+1.1)	+1.3-2.5 (+1.7)	+1.3-2.9 (+2.1)
		Spring	+0.7-1.2 (+0.9)	+0.9-2.1 (+1.5)	+0.9-2.3 (+1.3)
		Summer	+0.7-1.3 (+0.9)	+1.0-2.1 (+1.6)	+0.8-1.9 (+1.4)
		Autumn	+0.8-1.3 (+1.0)	+1.1-2.2 (+1.5)	+1.0-1.9 (+1.4)

Climate scenario (Representative Concentration Pathway)	Climate variable	Season	Projected change from 1986-2005 baseline (25^{th}- 75^{th} percentiles; 50^{th} percentile in brackets)		
			Near term	Mid-century	Late-century
			2016-2035	2046-2065	2081-2100
RCP 4.5 (Intermediate-emissions scenario)	Precipitation (%)	Winter	-1.2-+8.1 (+5.3)	+2.5-11.3 (+7.5)	+5.1-15.1 (+10.8)
		Spring	-2.0-+7.9 (+3.1)	+3.3-14.3 (+8.5)	+6.6-20.4 (+8.8)
		Summer	-3.1-+9.4 (+3.1)	-1.4-+12.2 (+3.9)	-2.1-+9.8 (+6.1)
		Autumn	-0.3-+5.5 (+1.6)	-0.3-+8.1 (+5.0)	-4.7-+9.5 (+1.9)
	Temperature (˚C)	Winter	+0.8-1.8 (+1.3)	+1.8-3.2 (+2.7)	+2.7-4.1 (+3.4)
		Spring	+0.8-1.4 (+1.1)	+1.6-2.6 (+1.7)	+1.9-3.1 (+2.5)
		Summer	+0.7-1.4 (+1.1)	+1.6-2.5 (+2.0)	+2.0-3.3 (+2.5)
		Autumn	+0.8-1.5 (+1.0)	+1.6-2.6 (+2.1)	+2.0-3.4 (+2.5)
RCP 8.5 (High-emissions scenario)	Precipitation (%)	Winter	+1.4-9.3 (+5.3)	+3.4-13.8 (+10.7)	+8.3-22.1 (+17.1)
		Spring	+0.7-8.7 (+5.2)	+4.0-13.1 (+9.0)	+8.6-22.5 (+14.9)
		Summer	-6.0-+5.9 (+2.5)	-2.4-+9.4 (+5.4)	-1.8-+15.6 (+6.3)
		Autumn	-4.2-+3.6 (-0.6)	-3.0-+8.5 (+3.8)	+0.4-+8.6 (+3.7)
	Temperature (˚C)	Winter	+1.0-1.8 (+1.4)	+2.7-4.1 (+3.4)	+5.3-6.7 (+6.0)
		Spring	+0.8-1.6 (+1.1)	+2.1-3.3 (+2.6)	+4.3-6.0 (+4.7)
		Summer	+1.0-1.6 (+1.2)	+2.4-3.4 (+2.8)	+4.2-6.0 (+5.3)
		Autumn	+0.9-1.6 (+1.2)	+2.3-3.7 (+2.9)	+4.2-6.0 (+4.8)

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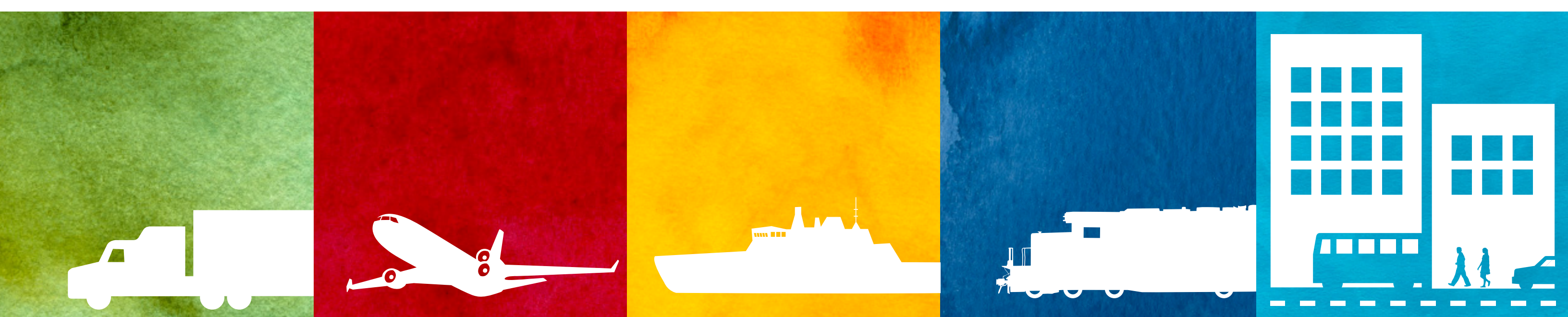

9 · Urban

CHAPTER 9: URBAN

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KEY FINDINGS

- **Enhancing redundancy (particularly across modes) in urban transportation networks increases resilience to climate change.** A redundant system gives travelers choices so that if one option performs poorly, other effective options are available. Redundancy becomes even more important in emergency situations (including those arising from extreme weather conditions) as it allows travelers to complete trips, and economies to function, even when major service disruptions occur.

- **Extreme weather events influence the perspectives and actions of urban decision-makers.** Events with severe socioeconomic impacts demonstrate to municipal decision-makers that human activity, short-sighted planning decisions, or failure to act, can exacerbate weather-related damages. Expropriating floodplain lands and re-routing roadways away from vulnerable areas are examples of policy changes made in response to extreme weather events in some Canadian cities.

- **"Low-regret" or "no-regret" adaptation strategies offer municipalities opportunities to enhance the resilience of transportation infrastructure at key points in infrastructure lifecycles, at little additional cost.** One example is enhancing stormwater management capacity to reflect probable future precipitation conditions, when existing infrastructure reaches a renewal period. These strategies also build public support for adaptation efforts if benefits are tangible, communicated clearly, and realized quickly.

- **The cost of resilient infrastructure is considered a barrier to implementing adaptive actions.** In terms of both capital and operational funding, innovative financing tools and intergovernmental partnerships could help promote adaptation when addressing Canada's growing municipal infrastructure deficit.

- **There is a need for structured collaboration among government departments, transportation agencies, emergency services, municipal councils, engineers, climate change specialists, and civil society.** Collaboration helps to ensure adaptation is a community-wide endeavour and highlights key interdependencies for the urban transportation sector (for example, with electricity and telecommunications providers).

- **Canadian cities are undertaking a number of resilience-enhancing initiatives.** Examples from Whitehorse, Prince George, Toronto, and Moncton demonstrate the diversity of adaptive strategies required to deal with the range of geographic and climatic challenges across the country. These case studies also suggest that, increasingly, urban practitioners are moving beyond risk assessment and beginning to implement adaptive practices and build resilient infrastructure.

1.0 INTRODUCTION

Urban transportation systems are vulnerable to both extreme weather events and the incremental impacts of a changing climate. Extreme weather disrupts and delays urban travel by washing out roadways and transit routes, and by damaging the electrical and communications systems upon which these modes rely. Increased temperatures cause pavement rutting, buckling of rail lines, and damage to infrastructure built on permafrost in Northern communities. These and other climate risks can affect the cost, efficiency, and safety of urban transportation in Canada.

In this chapter, urban transportation refers to all modes of transportation that carry people and goods within cities and, more broadly, metropolitan areas. This includes infrastructure and vehicles (automobiles, buses), rail transit (including metros, light rail transit [LRT], and commuter rail), and active modes, such as walking and cycling. Note that airports, regional and national rail systems, marine ports, and ferry services[3] are discussed in regional chapters of this report.

The focus of this chapter is on the vulnerability of urban transportation to the impacts of both gradual changes in climate and extreme weather events, taking into account the interactions between cities' concentrated infrastructure, services, and populations. The chapter also explores current efforts Canadian municipalities are making, and those planned for the future, to increase transportation resiliency. While some of these adaptations can be costly, many can be classified as "no-regret" or "low-regret" actions – strategies which involve few additional costs, produce co-benefits, or prevent higher future costs. Integrating climate considerations into decision-making processes (i.e. mainstreaming), for example, in the development of Official Plans, financial management processes, and infrastructure investment decisions, makes it easier to identify this type of adaptation.

Statistics Canada has recently replaced the term "urban centre" with "population centre." There are three categories, including:

- Small population centres (with populations between 1,000 and 29,000);
- Medium population centres (between 30,000 and 99,000); and,
- Large population centres (populations exceeding 100,000) (Statistics Canada, 2011a).

This chapter primarily focuses on the last two categories, although "urban centres" and "population centres" are used interchangeably.

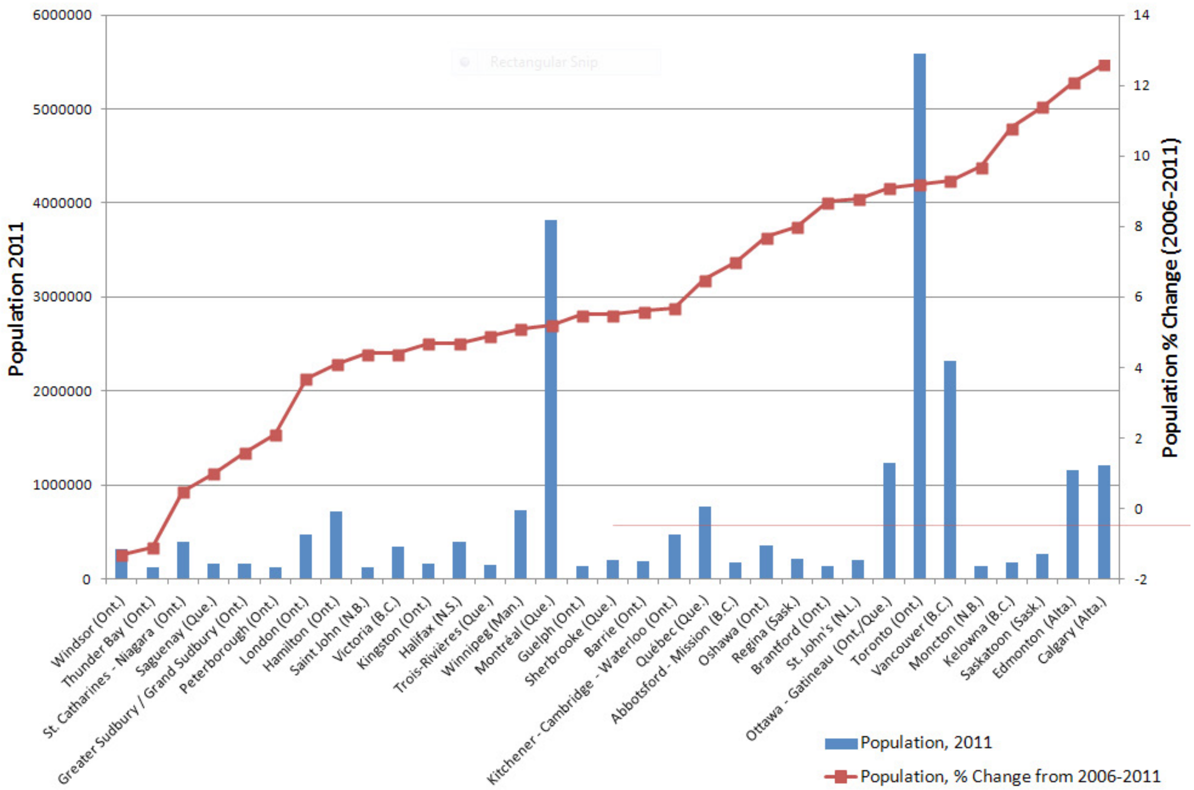
Recognizing that research examining climate impacts on urban transportation is limited in Canada, this chapter also draws upon relevant research from the United States, to supplement domestic content where appropriate.

1.1 TRENDS IN URBAN CANADA

Canada is growing increasingly urban. In the 2011 national census, 81 percent of Canadians indicated that they lived within medium or large population centres. Population trends suggest that the nation's largest urban areas – known as Census Metropolitan Areas (CMAs) – are growing rapidly, largely as a result of their ability to attract economic generators such as financial services, research and development agencies, and tourists, as well as newcomers to Canada (Filion and Bunting, 2010). Figure 1 presents the population growth in Canadian CMAs from 2006-2011.

[3] Ferries provide important transit services only in a few urban centres in Canada (e.g., Halifax and Vancouver).

Figure 1: Canadian CMAs with the highest growth rates from the 2006 National Census to the 2011 National Census. (Source: Statistics Canada)

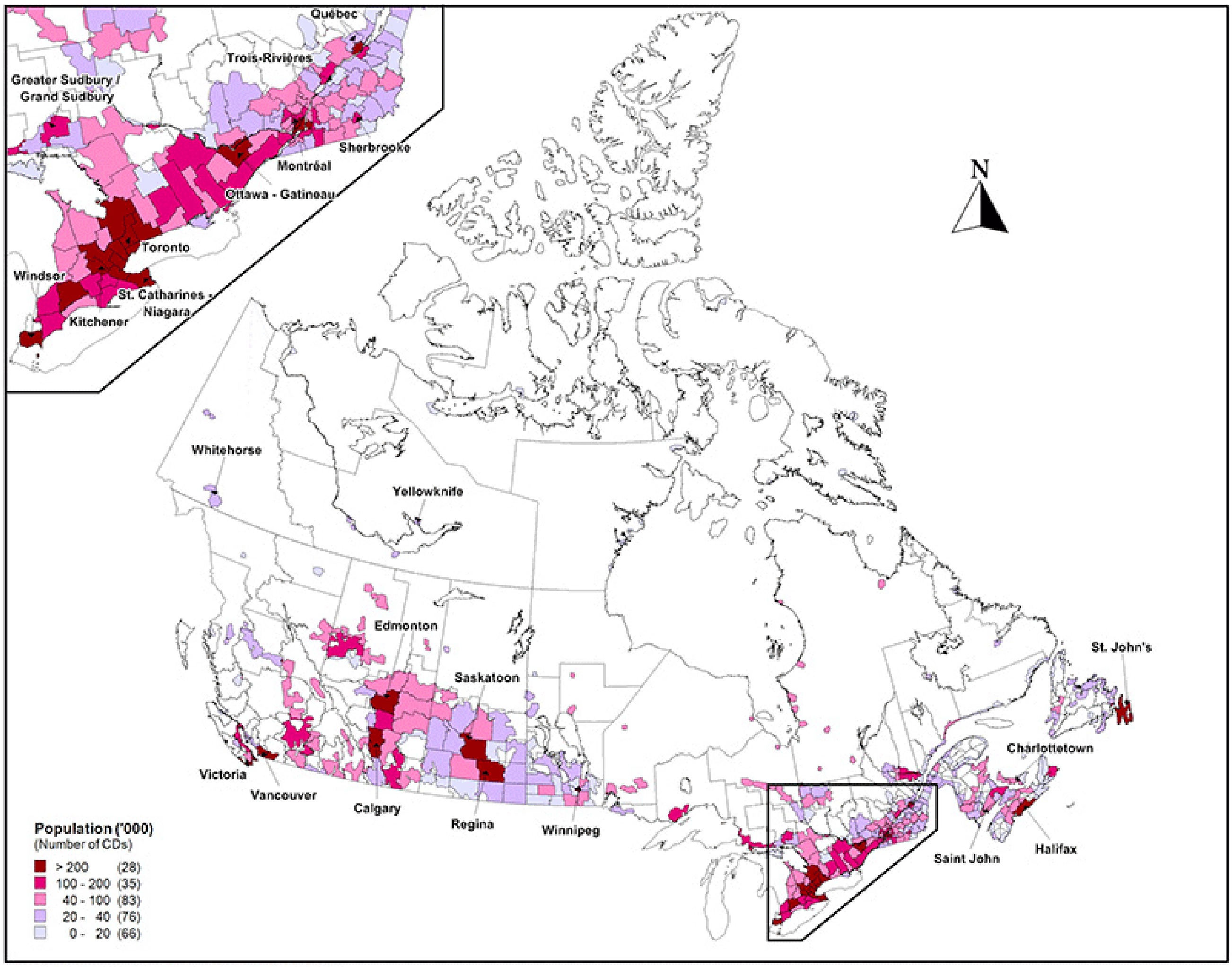


Both large and mid-sized cities are leading the urbanization movement in Canada. While the greater metropolitan areas of three cities (Montreal, Toronto, and Vancouver) now account for 35 percent of the Canadian population (Postmedia News, 2012), many smaller cities have experienced significant growth as well (e.g., Saskatoon, Kelowna, and Moncton). This is a trend experts expect to continue well into the 21st century. Thus, adapting to climate risks in Canadian cities will occur in tandem with managing urban population growth.

The degree to which Canadian cities will be affected by climate change and their capacities to adapt varies considerably. "Adaptive capacity" is a function of many factors, including geography. CMAs are distributed in a number of climate regions, including two in Canada's north (Whitehorse, Yukon, and Yellowknife, Northwest Territories), that face specific challenges related to rapid warming and thawing permafrost (see Chapter 3).

Canada's urban development in the postwar period has been characterized by low-density, sprawling suburban development outward from traditional downtown cores, which encourages (and often requires) the daily use of automobiles (Blais, 2013). Road congestion is taking an increasingly heavy toll on Canadian urban regions, accounting for $6 billion to $11 billion in lost economic productivity annually in the Greater Toronto and Hamilton Area, and $500 million to $1.2 billion annually in the Metro Vancouver area, depending on the specific metrics applied (Dachis, 2013; Dachis, 2015). However, many Canadian municipalities have begun to recognize the importance of compact and walkable neighbourhoods for improving the efficiency and sustainability of their urban environments (Ontario Ministry of Infrastructure, 2013; Metro Vancouver, 2011; Haider et al., 2013). As a result, there is a general movement to build "up" rather than "out," and population density is increasing along with population growth: in CMAs, population density increased by an average of 6 percent from 2006-2011 (Statistics Canada, 2011a; see Figure 2).

Figure 2: Urban density and agglomerations in Canada. (Source: Statistics Canada)



When assessing climate impacts on cities, density (of both population and infrastructure) is a complicating factor. Localized impacts, such as strong winds and heavy rainfall, disrupt a higher volume of traffic and economic activity, and affect more individuals and infrastructure components in urban centres than in less densely-populated areas (Revi et al., 2014; Solecki et al., 2011).

The deteriorating condition of municipal infrastructure further complicates the ability of Canada's highgrowth and increasingly dense cities to accommodate a growing population. The 2016 Canadian Infrastructure Report Card (CIRC), which assessed the condition of Canada's municipally-owned infrastructure, graded 14 percent of sidewalks, roads, and bridges, as "poor" to "very poor", with a total replacement value of $50.4 billion. The CIRC provided these same grades to 17 percent of public transit infrastructure (vehicles, mobile technology, security systems, signalization equipment, and terminal facilities), with a replacement value of $9 billion (Canadian Infrastructure Report Card, 2016). The report indicated that under current investment/maintenance conditions, most urban transportation infrastructure will require significant and increasing investment as it ages – even infrastructure presently in "fair" to "very good" condition (Canadian Infrastructure Report Card, 2016). The pressure placed on this infrastructure by climate change is likely to expedite the need to replace or upgrade older assets.

Transit ridership per capita in Canada is also growing annually (Canadian Urban Transit Association, 2012), while rates of auto ownership in CMAs are decreasing (Perl and Kenworthy, 2010). Transit is attracting greater attention from all levels of government in Canada, with federal and provincial spending support for urban transit in Canada growing at a rate of 5.2 percent annually since 2008 (Transport Canada, 2013). This is consistent with a broader international trend in urban governance to enhance public transportation modes as a method to reduce traffic congestion and improve public health (Bradford, 2008).

Finally, it is worth considering the interactions of multiple infrastructure systems in cities. Vehicles and at-grade rail systems rely heavily on drainage infrastructure to manage storm runoff. Rail transit networks in cities such as Calgary, Edmonton, Toronto, and Montreal depend on reliable electricity to power vehicles and communications networks. Vehicles and bus transit systems also rely on municipal electricity and emergency response resources for traffic signals and safety. This provides important context for this chapter, as both the public and private sectors in Canada are challenged to maintain or improve this array of interrelated urban infrastructure while simultaneously enhancing the resilience of transportation networks to changing climate conditions.

1.2 ADAPTATION TO A CHANGING CLIMATE

A number of strategies can be used to reduce the impacts of observed and anticipated changes in climate and extreme weather on urban transportation systems. The strategies discussed in this chapter fall into the following general categories:

- Investing in more resilient materials, infrastructure, and operational practices for transportation infrastructure;
- Improving redundancy within transportation networks – this refers to the availability of multiple paths or modes for urban travel with similar user costs;
- Updating the climate design criteria used in engineering standards to better reflect future conditions;
- Improving land use policies and controls (e.g., zoning amendments or construction requirements in vulnerable areas); and
- Enhancing the resilience of communities to extreme weather and climate effects through social adaptations.

2.0 CLIMATE AND URBAN TRANSPORTATION

Understanding the historical interactions of climate, weather, and geography are important to determine how climate change will affect urban transportation in Canadian cities in the 21st century. Location is an important factor in urban vulnerability to climate change, as many cities in Canada are located in low-lying areas next to significant bodies of water (Filion and Bunting, 2010). Floodplains, coastal regions, and other vulnerable areas could experience significant flooding, erosion, and infrastructure damage as a result of a changing climate and more frequent extreme weather events (Revi et al., 2014). While today's planning provisions often restrict development in vulnerable areas, this legacy of urban vulnerability persists, and is heightened by increasing population densities. Understanding how cities have dealt with climate impacts in the past helps vulnerable cities make informed decisions and investments, in order to adapt to emerging climate conditions.

This section provides an overview of climate and weather-related impacts on urban transportation in Canada, and projected climate conditions for the 21st century. Regionally-specific discussions of climate can be found in other chapters of this report.

2.1 CLIMATE SENSITIVITY OF URBAN TRANSPORTATION

Much has been learned about how to adapt to severe weather across all modes of urban transportation in Canada. Some examples are explored in this section.

REGINA CYCLONE, JUNE 1912

The Regina Cyclone, which occurred on June 12th, 1912, remains the most destructive tornado in Canadian history. It killed 30 residents, left 2500 homeless, and resulted in $1.2 million (approximately $25 million in 2015 dollars[4]) in property and infrastructure damage (Environment Canada, 2013a; Saskatchewan Archives Board, 2011). The damage was so significant that it took the municipality 40 years to pay back the debts it incurred (Saskatchewan Archives Board, 2011). The loss of the Canadian Pacific Railroad freight depot was particularly detrimental. The cyclone flipped railcars and destroyed grain warehouses, flattening a keystone of Western Canada's grain transportation network and affecting cities across the country that relied on western grain (Martin, 2012;).

In the century since this event, emergency management and communication protocols have changed significantly (including the use of electronic and social media to warn operators and travelers of impending threats), and urban building codes and materials are much more resilient to wind and rain (Martin, 2012). While the damage and disruption associated with a similar event would likely be severe, the transportation and other infrastructure impacts of a tornado would not be as devastating today thanks to more stringent building codes and improved materials (Martin, 2012).

FRASER RIVER VALLEY FLOOD, SPRING 1948

An unusually rapid warming of a heavy mountain snowpack caused the Fraser River, in British Columbia, to flood in May and June 1948. Floodwaters engulfed 2,300 homes, leaving 16,000 homeless and 10 dead (Robinson and Cruikshank, 2006). The estimated damage was $20 million (approximately $220 million in 2015 dollars) (Environment Canada, 2010).

The network of dykes set up to protect the urban areas of Chilliwack, Mission, and New Westminster were considered adequate for minor flood protection, but were unable to withstand the flood's high-water levels. On June 10, the river reached a peak height of 7.6 m in Mission, flooding streets and nearby highways, impeding vehicles, pedestrians, and two rail lines running through the town (McLean et al., 2007; Environment Canada, 2010). While only 0.5 percent of the 1,375-km floodplain is at risk of flooding today, this high-risk area includes a number of urban centres, and is home to two airports and key segments of highway and railway (Environment Canada, 2010).

Governments and decision-makers learned several lessons in the aftermath of the Fraser River floods. Better regional coordination, emergency planning, and awareness have catalyzed municipal, provincial, and federal governments to invest $300 million since 1948 to improve dykes and other flood-prevention measures in the region (to withstand a 200-year flood event); as a result, the adaptive capacity and resilience of these communities has been increased (McLean et al., 2007).

While significant improvements in flood control have been made, the Fraser Valley's urban regions face heightened risks to similar or more significant events in coming decades as a result of a changing climate.

[4] All conversions of historical to contemporary dollar values in this chapter have been derived from the Bank of Canada's Inflation Calculator, which provides conversions via consumer price index data. This tool can be found online at http://www.bankofcanada.ca/rates/related/inflation-calculator/.

Figure 3: Flood of the Fraser River at Mission, 1948. (Source: Environment and Climate Change Canada)

HURRICANE HAZEL, GREATER TORONTO AREA, OCTOBER 1954

Hurricane Hazel, which hit the Greater Toronto Area (GTA) in October of 1954, may be Canada's best-known weather-related urban disaster, and remains one of the most costly storms in the region's history. A wet autumn season left Ontario's soils supersaturated (Environment Canada, 2013a), which worsened the impact of 210 mm of rain that fell in a 36-hour period. Severe flash floods killed 81 people (Toronto and Region Conservation Authority, 2016). Damages totaled $100 million (approximately $900 million in 2015 dollars), half of which was spent replacing damaged or destroyed transportation infrastructure (Robinson and Cruikshank, 2006).

Disruptions to transportation systems were significant:

- Many train routes were delayed or otherwise affected, and a CNR railcar was overturned (Environment Canada, 2013a).
- CNR reported a dramatic increase in train travel during the storm due to widespread road flooding. 14,000 people traveled by train during Hurricane Hazel, compared to the daily average of 1,000 (Environment Canada, 2013a), demonstrating the importance of redundant transportation options in maintaining mobility during extreme events.
- Major flooding and washouts occurred on Highways 400, 11, and 12, stranding motorists. Sections of these highways, in the storm's peak, were under approximately 1m of water.
- A total of 40 bridges were damaged and 10 were de-commissioned. Many bridges serving key arterials, including connections over the Don River, York Mills, and Bayview Avenue, were severed, causing considerable social disruption (Environment Canada, 2013a).

The GTA took adaptive action after Hazel to address the hurricane's immediate effects and reduce vulnerability to similar future events. The city placed specific focus on emergency management policy and infrastructure decision-making. For example, the proposed location of Toronto's Gardiner Expressway route was amended, elevating the roadway and setting it back further from the shore of Lake Ontario. This busy highway running through downtown Toronto, yet to be built in 1954, would have been almost entirely washed out by a hurricane of this magnitude if built as initially planned (Environment Canada, 2015). In Hazel's wake, the City also placed greater emphasis on restoring transit services in a timely manner to alleviate road congestion during and after emergencies (Environment Canada, 2015).

Hurricane Hazel also shifted decision-makers' perspectives in Ontario. They no longer framed natural disasters as "acts of god" – rather, an important and transformative link was made between weather-related damage and planning decisions (Henstra, 2011). Hazel prompted the Toronto and Region Conservation Authority to make many policy changes that resulted in greater resilience to extreme weather and flood events. Specifically, the Authority:

- Expropriated floodplain lands near watercourses and prevented development in these areas;
- Increased the amount of water-absorbing green space in the city; and,
- Improved watercourse management infrastructure and techniques (Robinson and Cruikshank, 2006).

Figure 4: Personnel of the Canadian Army clearing away debris in the aftermath of Hurricane Hazel. (Source: Library and Archives Canada)

Prior to Hurricane Hazel, volunteer groups typically led storm clean-up efforts in Ontario. Hazel gave municipalities the impetus to leverage provincial and federal governments for resources to adequately prepare for and recover from extreme weather events (Robinson and Cruikshank, 2006).

EASTERN CANADA ICE STORM, JANUARY 1998

From January 4th to 10th, 1998, significant amounts of freezing rain accumulated from eastern Ontario to Nova Scotia. Greater than 100 mm of ice fell in more than 80 hours of precipitation, leaving over 4 million people without electricity, and resulting in significant transportation disruptions. Electrical wires, utility poles and tree branches blocked roadways, and power outages disrupted traffic signals. Roads were closed and public transit services were delayed and cancelled, while icy conditions caused accidents and made travel dangerous (Bertin, 1998). More than 16,000 Canadian Forces personnel were deployed to manage the aftermath; Environment Canada estimated the initial insurance claims to be more than $1.5B, with a total exceeding $3 billion (Environment Canada, 2013b).

Figure 5: Fallen tree branches following the ice storm. (Source: Environment and Climate Change Canada)

Following the ice storm, several measures were implemented based on the lessons learned. For example, the province of Quebec adopted legislation requiring all municipalities to prepare emergency plans and created better communication between the provincial and municipal governments (Institute for Catastrophic Loss Reduction, 2016). Hydro-Quebec also took measures to prevent power outages such as reinforcing transmission towers, adding additional hydro lines and burying power lines (The Canadian Press, 2008). While these measures were largely focused on public health and safety, better emergency planning, communications and electricity systems also support the resiliency of transportation systems.

HURRICANE JUAN, HALIFAX, SEPTEMBER 2003

Cities in Atlantic Canada have also experienced severe impacts from extreme weather events, and climate models suggest the frequency of these events will increase in this region in the 21st century (AMEC Inc., 2011). Hurricane Juan, that struck Halifax on September 29th, 2003, was the most destructive storm in the city's history, due to effects of storm surge (temporary sea-level rise), intense flooding, and strong winds (Environment Canada, 2013a). Sustained wind speeds reached a maximum of 160 km/h. Halifax Harbour experienced wind gusts up to 230km/h and storm surges of 1.5-2m, leading to severe shoreline erosion and the loss of railway tracks (Bowyer, 2003a). Containers were blown off ships in the port, and several rail cars were washed into the Atlantic at the Dartmouth rail yard (Bowyer, 2003c). The storm's volatility and disruption to transportation services contributed to the closure of businesses and schools for five days (Bowyer, 2003b). The estimated cost of damages related to Hurricane Juan totaled $200 million (Environment Canada, 2013a). The event prompted decision-makers in Atlantic Canada to improve planning and preparation processes for extreme weather events: clearer channels were created for communication and coordination among provincial and local emergency response departments, and hurricane-specific training for emergency personnel was mandated in the immediate aftermath (Government of Nova Scotia, 2003).

Figure 6: Storm surge causes wharf damage in Halifax Harbour. (Source: Environment and Climate Change Canada)

FLOODING, GREATER TORONTO AREA, JULY 2005 AND JULY 2013

Several extreme summer storm events have caused substantial disruption and damage to the Greater Toronto Area (GTA). In August 2005, intense rainfall and flooding cost the City of Toronto $47 million (insurance covered the additional $500 million in damages) (McLeod, 2011). One major culvert on Finch Avenue sustained $4 million in damages due to wash-out (City of Toronto, 2014; McLeod, 2011; see Figure 7).

Figure 7: A section of Finch Avenue washed out during the heavy rainstorm of August 19, 2005. (Source: City of Toronto)

Similarly, during a severe storm in July 2013, 126mm of rain fell on the GTA within two hours, resulting in $850 million in insurance claims (Environment Canada, 2014). While the hourly rate of rainfall (intensity) was higher during this event than during Hurricane Hazel, damage was significantly less severe due in part to improvements in Ontario's emergency planning policy framework after Hazel (Henstra, 2011; Aulakh, 2013). Transportation disruption was significant nonetheless. Subways were closed due to flooding, GO trains were evacuated by police boats, and drivers faced washed-out roads. However, transportation networks in the city were almost completely restored by the following day (CBC News, 2013). A number of adaptive actions were identified in the aftermath of this crisis, including the development of more robust flood management and prevention plans for the Don Valley, and the installation of emergency back-up power at key bus and locomotive maintenance facilities.

CALGARY FLOOD, JUNE 2013

An important final example relates to the flooding of the Bow River in Calgary, Alberta in June 2013. At the storm's peak, 200mm of rain fell within approximately 16 hours on supersaturated soil and, in some places, still-frozen ground (Davison and Powers, 2013). As Canada's costliest climate-related disaster to date, damages in Calgary are estimated to surpass $6 billion. Damage included bridges, culverts, roads (over 1,000 km) and public transit infrastructure (Environment Canada, 2014). In addition, scour (the removal of supporting earth by fast-moving water) caused the Bonnybrook Bridge to partially collapse, leaving six Canadian Pacific Railway freight cars hanging over the Bow River; shortly thereafter, the bridge was de-commissioned (Canadian Press, 2014). The Transportation Safety Board

(2014) ruled that "unprecedented flood water was to blame for the derailment," and recommended more frequent bridge inspections, reduced train speeds in scour-prone areas, and investment and research into early-detection technologies for structures vulnerable to scour and erosion.

Figure 8: Rail cars sit on the collapsing bridge after a train derailed on Bonnybrook Rail Bridge on June 27, 2013. (Source: Transportation Safety Board of Canada)

2.2 CLIMATE TRENDS AND FUTURE PROJECTIONS

This section provides a summary of projected climate conditions for 21st-century Canada, with a focus on climate elements of particular relevance to urban transportation. These include:

- Greater variation and extremes in seasonal and annual air temperature;
- Changing precipitation patterns;
- Increasing intensity and duration of wind speed, particularly during storm events;
- Changing patterns of sea and lake ice;
- Increasing permafrost degradation;
- Changing water levels, along both coastal and inland waterways; and,
- Combinations of these changing climate elements.

AIR TEMPERATURE

Average air temperature in Canada increased by 1.5˚C from 1950-2010, and is projected to increase by about 1.5-2.5˚C by mid-century (in a low-emissions scenario), with increasing frequency of extreme heat and decreasing frequency of extreme cold (Bush et al., 2014). In cities, these trends are exacerbated by the urban heat-island effect, referring to the difference between surface and air temperatures (typically 10-15˚C for surfaces and 1-3˚C for air) in urban centres and surrounding rural areas. The heat island effect occurs due to a combination of factors (Figure 9), including:

- The lack of vegetation in cities (which regulates temperature);
- The low solar-reflective capacity of urban infrastructure;
- The high heat-absorbance of urban materials (e.g., black asphalt) – highly-developed areas have less surface moisture available for evapotranspiration (which cools surrounding air) than natural ground cover, due to impervious surfaces like pavement and concrete (75-100 percent cover in most cities);
- Anthropogenic (human-caused) heat production (e.g., air conditioning, vehicles, industrial activities); and,
- Urban topography (e.g., narrow streets limit the capacity of buildings to radiate heat at night and limit the passage of cooling winds) (United States Environmental Protection Agency, 2008).

Urban heat islands have implications for the integrity of transportation infrastructure, particularly pavement. Figure 10 provides an example of an urban heat island map for Montreal, Quebec.

Figure 9: An illustration of an urban heat island profile. The impacts of heat waves tend to be greater in urban, rather than suburban or rural areas, likely owing to the 'heat island' effect. (Source: Natural Resources Canada)

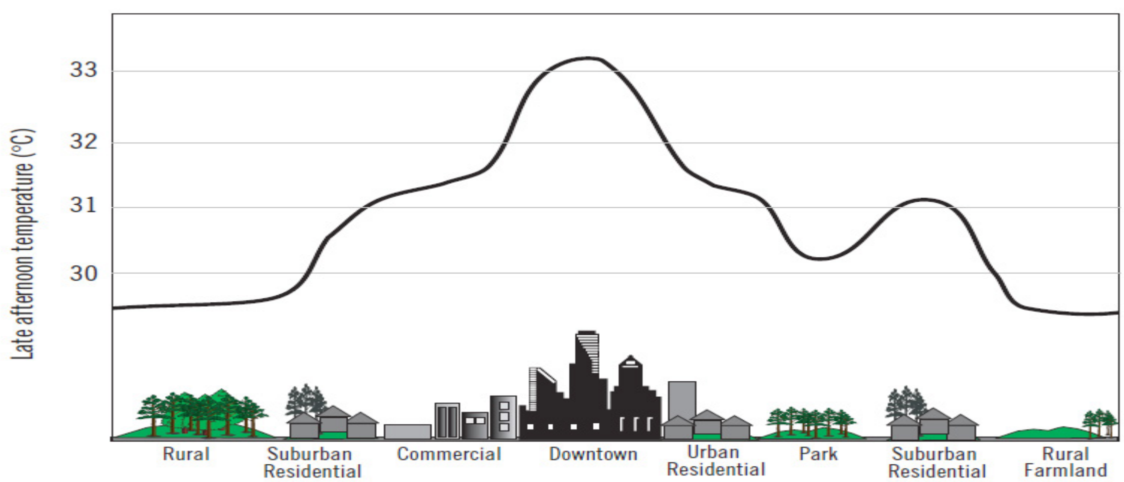
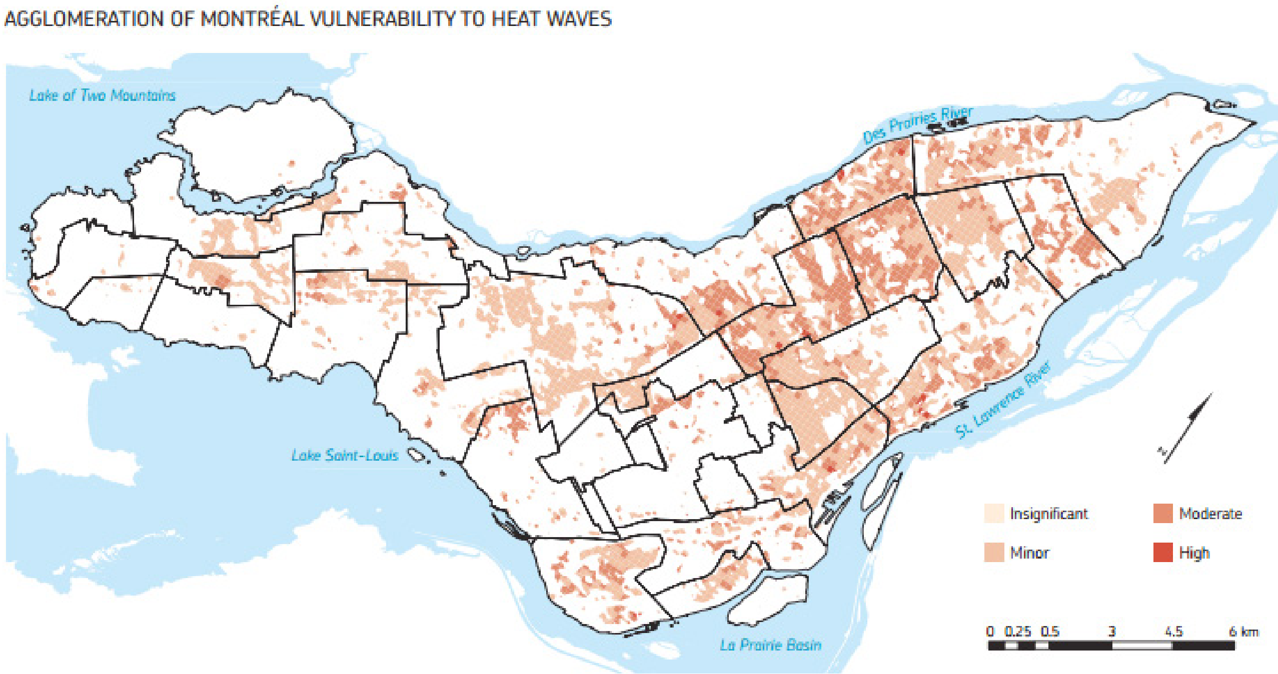


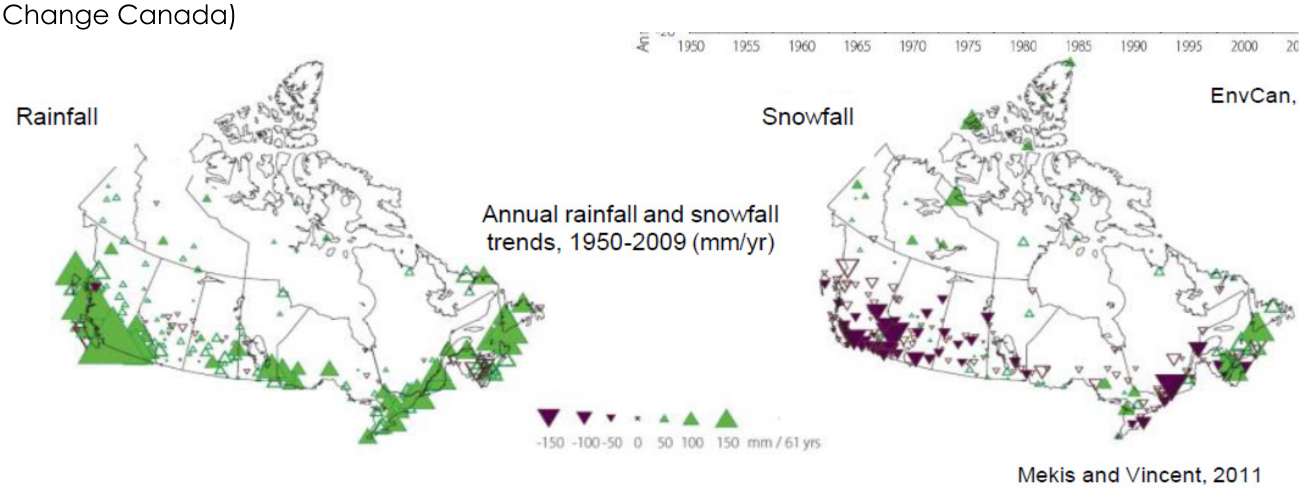
Figure 10: Urban heat island map for Montreal, Quebec. (Source: City of Montreal)



PRECIPITATION

Projected changes in precipitation in Canada, include an increase in British Columbia and Atlantic Canada, as well as changes to the seasonal distribution of precipitation across the country (Bush et al., 2014). Precipitation is expected to increase in all seasons across most of Canada, with the exception of a summer decline in the southwest (Bush et al., 2014). Figure 11 shows changes in precipitation patterns in Canada over the last 59 years.

Figure 11: Changes in precipitation in Canada, 1950-2009. (Source: Environment and Climate Change Canada)



WIND

Changes in patterns of wind relate to temperature and precipitation trends and extremes. One study suggests that the intensity of average daily wind speed will increase by 10-30 percent across Canada by the late 21st century, compared to baseline conditions in the period from 1955-2009 (Cheng et al., 2014). However, the extent of these changes remains uncertain.

LAKE, RIVER, AND SEA ICE

Changing patterns of lake, river, and sea ice pose risks to urban regions next to watercourses and oceans. The extent and seasonal duration of inland ice is likely to decrease as winters warm; however, shifting patterns of spring break-up pose risks in terms of ice-jam flooding and infrastructure management on rivers and lakes (Bush et al., 2014). For example, in spring 2015, this phenomenon prompted the emergency evacuation of Perth-Andover, New Brunswick (see Chapter 8) (Canadian Press, 2015a).

Figure 12: Ice jam prompts evacuation order in Perth-Andover in spring 2015. (Source: Perth-Andover Fire Department)

WATER LEVELS

Both inland and ocean water levels are projected to change significantly in Canada, although the direction of change will vary geographically. While most of the Atlantic and Pacific coasts will experience sea level rise, much of the northern coast will experience relative sea-level decline due to a phenomenon known as "glacial isostatic rebound," in which land formerly covered by glaciers slowly decompresses and rises (Atkinson et al., 2016). While water levels on some inland waterways are expected to decline (such as the Great Lakes) as a result of greater evaporation, others will rise, at least temporarily (Bush et al., 2014).

PERMAFROST

Thawing permafrost is a significant issue in Canada's north, where infrastructure is built on soils underlain by permafrost (Prowse et al., 2009; Transportation Association of Canada, 2010) (see Chapter 3).

Temperature variations may also change the nature of transportation hazards in winter. For example, areas traditionally challenged by snowfall may face increased freezing rain and black ice.

2.3 CLIMATE RISKS TO URBAN TRANSPORTATION

Roadways, rail transit systems, and active transportation networks are vulnerable to climate risks and extreme weather in two key ways. First, operations can be disrupted by extreme weather events and obstructed rights-of-way, as described in Section 2.1. Second, infrastructure is structurally and physically vulnerable to the increasing range of some climate variables (i.e. temperature and precipitation) expected under future conditions. Infrastructure may be exposed to weather extremes unaccounted for in original engineering designs, which assumed that past climate extremes accurately represent future conditions (see Box). Severe weather and shifting "average" conditions can therefore shorten infrastructure life spans, reduce performance, and increase maintenance and operating costs (McLeod and Stevanovic-Briatico, 2014). The following sections provide an overview of climate impacts to urban transportation systems summarized in Table 1.

REGULATORY VULNERABILITIES: CODES, STANDARDS, AND RELATED INSTRUMENTS (CSRI)

The failure to sufficiently consider changing climate conditions in the development and application of engineering and land-use standards might be termed "regulatory vulnerability." A survey of case studies which used the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol[5] considered the role codes, standards and related instruments (CSRI) play with respect to resilient infrastructure (Engineers Canada, 2012). The survey found that some jurisdictions apply national codes directly; some modify national codes; and others develop location-specific codes to reflect local geography and risk-tolerance preferences. The report concluded that adopting a "climate adjustment factor" into CSRI at the national level may not revolutionize local practices, but the authors suggest that frequent updates based on climate model projections would assist practitioners in adapting their CSRI. Other inputs to CSRI, including professional judgment and management direction based on local conditions; accepted practices of the era; maintenance, operability, and procurement considerations; and other social, environmental, and economic factors, were considered robust in Canada (Engineers Canada, 2012).

[5] The PIEVC Engineering Protocol, led by Engineers Canada, was developed as a 5-step process to analyze the engineering vulnerability of individual infrastructure systems based on current climate and future climate projections. Further information can be found at http://pievc.ca/.

3.0 URBAN ROAD INFRASTRUCTURE

Urban road infrastructure includes roads for vehicles, (i.e. trucks and buses, whether electrified trolleys or diesel); electricity for traffic signals, signage, and lighting; bridges; and stormwater management infrastructure (culverts, ditches, etc.). While per capita vehicle-km travelled (VKT) in Canadian cities is modestly declining (Perl and Kenworthy, 2010), roadways remain critically important to urban economies for the movement of both freight and passengers. This is particularly the case in cities without strong transit links between urban centres and outlying suburban communities.

PRECIPITATION

Precipitation affects urban roads and bridges in a variety of ways. Washouts (due to soil/slope instability when water infiltrates a roadway's substructure) and flooding often result in delays, detours, and closures that reduce mobility and increase travel times for both automobiles and bus transit (United States Federal Highway Administration, 2015; Andrey and Mills, 2003). High-intensity precipitation events disrupt power to traffic signals and other supporting infrastructure, cause roadway disruptions when runoff volumes exceed the capacity of culverts and runoff ponds, and overwhelm the permeability of construction materials, reducing road safety (increasing the risk of accidents), and increasing the risk of bridge scour (Andrey and Mills, 2003; Transportation Research Board, 2008; Revi et al., 2014). For example, on May 29, 2012 in Montreal, 45 mm of rain fell in under an hour, resulting in flash flooding and closing streets.

While the proportion of snow as winter precipitation is likely to decline throughout Canada over the 21st century (Bruce, 2011), extreme winter storms producing heavy snowfall will continue to disrupt roadways and transit operations. This can result in significant service delays, as was the case in Ottawa, in 2013 when heavy snowfall caused buses to lose traction and become stuck (CTV News, 2013).

Freezing rain is likely to become more frequent in many parts of Canada (Cheng et al., 2011), causing ice build-up, road blockages, and power outages due to fallen tree branches and utility lines, and posing risks to road safety in urban areas (Andrey, 2010; Andrey et al., 2013). Increased salt usage to combat icy road conditions corrodes concrete infrastructure, and carries negative implications for the well-being of roadside ecosystems and urban water supplies (McLeod and Stevanovic-Briatico, 2014).

TEMPERATURE

Climate-induced stress to pavement mixtures is a growing issue for road operators. While most asphalt and concrete used in Canada is designed to withstand temperatures between -20˚C and 30˚C, projected temperatures for many Canadian cities in the 21st century exceed this range. In extreme heat during summer months, softening, rutting, flushing, and bleeding of asphalt are expected to increase in frequency and severity (Mills and Andrey, 2002). Softening and rutting occur when vehicles depress hot pavement (Mills et al., 2009). Bleeding refers to asphalt moving above a pavement's surface treatment (the waterproof layer upon which vehicles drive); flushing refers to the upward movement of asphalt to the fringe of the surface treatment, though not beyond the aggregate seal. While bleeding leads to more serious roadway damage, both phenomena reduce pavement integrity (Texas Department of Transportation, 2006). Softened pavement also leads to reduced maximum loads on municipal roadways, reduced ride quality and vehicle performance, increased maintenance costs, and reduced lifespan of roads, bridges, and culverts (McLeod and Stevanovic-Briatico, 2014). In extreme heat, trucks and buses wear more heavily on roads than automobiles due to their more substantial chassis and passenger loads, exacerbating pavement rutting and shearing issues (Savonis et al., 2008).

Extreme heat also produces heat stress for construction workers (Transportation Research Board, 2008); on especially hot summer days, it may not be safe or possible to carry out construction work during peak daytime hours (United States Federal Highway Administration, 2015).

Bridge infrastructure is also vulnerable to extreme heat. Bridges are designed to withstand some expansion and contraction through the use of flexible materials embedded between fixed points. However, as temperatures increase, the limits of these expansion joints can be exceeded, displacing material or cracking deck materials, especially at the interface with fixed points. This cracking can lead to substantial bridge deterioration, resulting in closures and lengthy detours (Cohen et al., 2005). In addition, both extreme heat and cold may result in malfunctioning traffic control signals (McLeod and Stevanovic-Briatico, 2014).

As seasonal temperature patterns shift, the frequency of freeze-thaw cycling is likely to increase throughout Canada, and the timing and onset of freeze-thaw events are likely to change, with implications for road infrastructure (Transportation Research Board, 2008). During periods of thaw, moisture seeps into small cracks, freezes and expands when cold returns, and melts (causing pavement weakness) during the next thaw (United States Federal Highway Administration, 2015). As a result, pavement is more likely to experience shearing (cracking) and rutting, reducing the strength and stability of roadways (Transportation Research Board, 2008; United States Federal Highway Administration, 2015). In northern climates, freeze-thaw cycling and temperature increases also contribute to further permafrost degradation, which poses risks to the stability of urban roads and their embankments (Woudsma et al., 2007; Transportation Association of Canada, 2010).

CHANGING WATER LEVELS

Bridge scour, which refers to the removal of supportive sand and rock sediment around bridges constructed over waterways (Transportation Research Board, 2008), has affected many Canadian jurisdictions during high-water events (Environment Canada, 2014). Similarly, flooding and storm surges pose erosion risks to coastal highways – this is particularly problematic in Atlantic Canada and British Columbia (AMEC Inc., 2011). Vancouver was recently named the 15th most-vulnerable city in the world to sea level rise, with likely impacts to road infrastructure by 2100 (at which point 1.1m of sea level rise is anticipated). These impacts include inundation, erosion, and washing-out of low-lying downtown streets (Mills, 2016).

WIND

Data suggest the intensity of wind gusts (on average and during extreme events) is likely to increase over the 21st century in Canada (Cheng et al., 2008), although with considerable regional variability (Cheng et al., 2014). Fallen debris (i.e. power lines, trees, and branches) from high winds can obstruct roadways, sidewalks, and cycling pathways (City of Montreal, 2015), while blowing snow disrupts visibility in winter months (Andrey et al., 2013). Strong winds may also temporarily close bridges – for instance, the Burlington Skyway near Hamilton, Ontario is closed when winds reach or exceed 85km/h (Craggs, 2014).

WILDFIRE

Changing patterns of temperature and precipitation affect the frequency and severity of wildfires, particularly in Canada's drier, western regions (i.e., the Prairies and British Columbia). Recent research suggests that the frequency of wildfires will rise over the 21st century, and that fire management agencies in both coastal and temperate areas may need to adapt their planning and response capacities to deal with potential changes in fire regimes (Wang et al., 2015). This has implications for transportation, particularly for emergency response planning. For example, during the catastrophic 2011 wildfires in Slave Lake, Alberta, emergency personnel successfully coordinated the evacuation of residents by road, despite the availability of only a handful of exit routes out of the town (which quickly became congested) and thick smoke. This success was attributed to planning and coordination amongst municipal departments and emergency personnel prior to the crisis (KPMG, 2012).

OPPORTUNITIES

There are also opportunities for road transport associated with climate change. In southern cities, for instance, construction seasons are likely to be longer, and winter road-maintenance costs are likely to be lower in warmer winters, despite an increasing proportion of freezing rain (Andrey and Mills, 2003; Fu et al., 2009). It remains to be seen, however, what impact increased freeze-thaw cycling might have on these cost savings.

4.0 URBAN RAIL TRANSPORTATION

Urban rail systems include subways, LRT, and streetcars. They also include urban freight systems, although information on the regional and national rail system can be found in the regional chapters of this report.

Ongoing and planned rail-transit projects, including those identified below, complement existing and well-used LRT and subway systems in Vancouver, Calgary, Edmonton, Montreal, and Toronto. Other jurisdictions with smaller populations are also beginning to recognize the benefits of investment in rapid transit. For example, the City of London is in the public consultation and mode-selection phase for rapid transit, and Victoria is in the planning stages of bringing LRT to its metropolitan area. These projects demonstrate renewed public interest in, and support for, rapid transit in general and rail-based modes in particular.

- **Toronto:** Eglinton Crosstown LRT and Scarborough subway extension (construction phase);
- **Kitchener-Cambridge-Waterloo:** ION LRT (construction phase);
- **The Greater Toronto and Hamilton area:** Electrification of the GO Transit network (planning phase); and,
- **Ottawa:** Confederation Line LRT (construction phase).

PRECIPITATION

Many urban rail systems rely on municipal electricity grids; therefore, locomotives and signals are vulnerable to power outages in extreme weather conditions (i.e. rainfall and snow). Track beds are also subject to a number of the same climate impacts as urban roadways, including reduced stability during flooding and erosion during extreme precipitation events (Mills and Andrey, 2002).

As with roads, precipitation can overload the stormwater management infrastructure that protects underground, surface, and elevated rail transit. Extreme weather events can result in flooding and inundation of rail systems, as was the case in Toronto in the summer of 2013 (Wooler, 2004). Extreme precipitation in Montreal during May 2012 (discussed in Section 3) also resulted in tunnel closures and the evacuation of several metro stations (City of Montreal, 2015).

TEMPERATURE

Rail infrastructure is prone to buckling in extreme heat, increasing the potential for sensor malfunctions, scheduling delays, speed restrictions, and – in extreme cases – derailment (Savonis et al., 2008). Tunnels used in underground rail transit systems can also experience operational challenges during extreme heat, including mechanical issues with ventilation. As a result, operators need to sufficiently consider passenger comfort, health, and safety (Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), 2002).

Extreme cold also affects urban rail. For instance, the Toronto Transit Commission (TTC) subway system faced several extreme-cold power outages in the winter of 2015, due primarily to broken water mains flooding tunnels (McLeod and Stevanovic-Briatico, 2014). Cold temperatures can also cause frozen track signal switches, delaying trains (Canadian Press, 2015b). However, this may become less problematic in southern cities if the frequency of cold days and nights decreases as projected (Bush et al., 2014).

CHANGING WATER LEVELS AND STORM SURGE

During periods of seasonal ice-jam flooding, railways adjacent to water and their embankments may be inundated, washed-out, or eroded. Bridge scour is also a risk for rail bridges, as suggested by Calgary's experience in the summer of 2013 (see Section 2.1).

WIND

High-intensity wind events also pose risks to rail infrastructure and operations, such as damage to overhead cables and tall signalization equipment, and rail-car blow-over (OFCM, 2002). Similar to roads, rail lines may also be obstructed by fallen debris causing service delays.

OPPORTUNITIES

Investment in rail transit can enhance the redundancy of urban transportation networks, providing mass transit options when roads are closed, unsafe, or congested (Box 1). Rail transit projects could also benefit from longer construction seasons, as winters shorten (Transportation Research Board, 2008).

BOX 1: REDUNDANCY IN URBAN TRANSPORTATION SYSTEMS

Redundancy is one method to enhance the resiliency of transportation networks to extreme weather and a changing climate. A redundant system allows travelers choices so that even when major service disruptions occur (e.g., extreme congestion or wash-out), other options are available, and travelers can complete their trips and economies can continue to function. For example, in major cities like Montreal and Toronto, if localized flooding causes the subway system to stop running, users can still travel by foot, bicycle, and on public buses. An opposite example is the nearly singular reliance of travelers in the Greater Toronto and Hamilton Area on Highway 401 for travel between Toronto and points east and west. If Highway 401 were closed, the alternative roadway and transit networks would be insufficient to maintain reasonable travel times and reliability.

Improving redundancy does not mean building additional roads, particularly above the level of current demand in corridors. In North American history, the construction of extra roads has often stimulated latent (hidden) demand for road capacity, and done little to reduce congestion, improve network efficiency, or address issues associated with urban sprawl (Duranton and Turner, 2011).

5.0 ACTIVE TRANSPORTATION

Walking and cycling networks are critical to the movement of people within Canadian cities. Public transit users, cyclists, and auto travelers are all pedestrians at some stage in their journeys, and pedestrian and cycling facilities provide the most reliable forms of connectivity within cities. Active modes have increasingly been a focus of investment at the municipal level in Canada, addressing climate change concerns from both mitigation and adaptation perspectives (Younger et al., 2008; Ayres, 2014). While the social and environmental benefits of active transportation are well-publicized in municipal planning documents, these modes are also becoming more attractive for short trips as a way to save time as Canadian cities become increasingly dense and traffic-congested.

Active transportation modes also offer an important form of redundancy to urban transportation networks (Box 1). Walking and cycling offer a "safety net," permitting travel when mechanized transport is temporarily unavailable. Given the benefits of active transportation in terms of public health, relative insensitivity to climate change impacts, and low capital costs and environmental impacts, many cities in Canada (and globally) are increasingly investing in these modes.

PRECIPITATION

Active transportation systems face many of the same vulnerabilities as roadways in terms of pavement degradation, storm-water management issues related to runoff and permeability, and associated operational disruptions (e.g., flooding and washout). This is especially true for sidewalks and bicycle lanes next to urban roadways, which make up the majority of active transportation infrastructure in Canada (Transport Canada, 2011).

There tends to be a modal shift away from walking and cycling during precipitation events – all forms of precipitation reduce the proportion of trips taken by active modes (Koatse and Rietveld, 2009). Similarly, pedestrian safety decreases in bad weather, with the number of outdoor injuries increasing dramatically in response to winter precipitation (including snow, rain, and freezing rain) (Morency et al., 2012). However, active transportation remains an important form of redundancy. Travelers are likely to walk in poor weather conditions if roads or transit lines are incapacitated, which means the volume of commuter (i.e. essential) trips is not significantly affected by severe weather (Koatse and Rietveld, 2009; Sabir et al., 2010).

TEMPERATURE

Extreme temperatures also affect the use of active modes. Walking and cycling on hot days requires more exertion and may pose health risks, particularly to vulnerable populations (such as the elderly) (Younger et al., 2008), a phenomenon worsened by the urban heat island effect (see Section 2.2). Some research (i.e. Sabir et al., 2010) suggests that during extreme cold, cyclists shift to public transit and walking, while the opposite is true during periods of extreme warm weather. However, other research (i.e. Koatse and Rietveld, 2009) has found that both extremely high and low temperatures are likely to reduce cycling activity.

CHANGING WATER LEVELS AND STORM SURGE

As with roadways, walking and bicycle paths (especially along coastal roads, or in ocean-side parks) are at risk of inundation and wash-out due to sea-level rise and storm surge (Mills, 2016).

WIND

Active transportation infrastructure tends to be less vulnerable to structural impacts than road and transit systems, due to the absence of heavy, motorized traffic. However, elevated portions of walkways and bikeways, as well as signage, can be damaged by high winds during extreme weather events (OFCM, 2002). Strong winds are also associated with lower levels of cycling (Koatse and Rietveld, 2009). High winds will also pose a safety hazard to cyclist and pedestrians, due to flying and falling debris.

OPPORTUNITIES

Warmer winters with less snow in many Canadian cities will provide longer seasonal access to walking and cycling infrastructure. Some Northern cities view climate risks to roadway infrastructure as an opportunity to enhance active modes. Whitehorse, for instance, has placed significant emphasis on active transportation in recent years and invested in high-profile cycling facilities. This is, in part, due to a projected increase in the length of the season in which cycling and walking is possible for most trips (Transport Canada, 2011).

Table 1: Overview of impacts to each mode of urban transportation in relation to the climate elements identified in this section.

Climate factor		Impacts on urban roads, bridges, sidewalks and supporting infrastructure (stormwater management, signals, electricity)	Impacts on urban rail infrastructure, operations and supporting infrastructure (stormwater management, signals, electricity)
Precipitation	More extreme rainfall/ snowfall events; higher average annual rainfall	• Roadway flooding/inundation/ erosion/washout • Blocked culverts leading to culvert failure • Road blockage and disruption from snow storms/ice storms/ rainfall • Substrate/slope instability due to increased soil moisture • Travel delays, detours, closures • Bridge scour/closures • Bus transit delays/detours • Overloading of stormwater management infrastructure • More frequent slick-road conditions (increasing risk of vehicular accidents) • Utility disruption (e.g., loss of power) • Fewer active transportation trips • Flooding of bus storage depots	• Obstruction of rail lines and track switches • Rail transit delays/line/tunnel/station inundation, flooding, and closures • Utility disruptions (e.g., loss of power) for electric locomotives and signalization equipment • Reduced rail bed stability during flood events • Rail embankment/crossing erosion during rainfall • Flooding of train storage depots
	More freezing rain events	• More frequent icy-road conditions (in winter) • Modal shift to public transit/ automobile from active transportation • Utility disruption (e.g., loss of power) • Increased salt usage – ecosystem effects; signal box malfunctioning; concrete corrosion	• Utility disruption (e.g., loss of power) • Obstructed rail lines (e.g., fallen branches) • Increased salt usage – ecosystem effects; signal box malfunctioning; rail-crossing corrosion

Climate factor		Impacts on urban roads, bridges, sidewalks and supporting infrastructure (stormwater management, signals, electricity)	Impacts on urban rail infrastructure, operations and supporting infrastructure (stormwater management, signals, electricity)
Air Temperature	Extreme heat	• Pavement and sidewalk softening/rutting/shoving/bleeding/flushing • Reduced passenger comfort/vehicle performance/lifespan of roads and sidewalks • Thermal expansion of bridges • Heat stress for labourers and active transportation users (impossible or unsafe daytime construction) • Traffic signal malfunctions • Higher road/vehicle maintenance costs • Decreased active mode share; modal shift to public transit/automobile • Increased electricity demand, leading to loss of power	• Rail buckling (speed restrictions, spillage, derailment, scheduling delays, sensor malfunctioning) • Sensor malfunction on rail tracks
	Extreme cold	• Traffic signal malfunctions • Decreased active mode share; modal shift to public transit/automobile	• Frozen track switches • Rail cracking • Utility disruptions (e.g., power loss, broken water mains causing tunnel flooding) for electric locomotives, signalization equipment, and tunnels
	Increasing and shifting freeze/thaw cycles	• Pavement shearing and rutting/pothole formation • Damaged stormwater management infrastructure (cracks and heaving)	• Damage to underground transit lines and tunnels
	Permafrost degradation (Northern)	• Winter road destabilization (e.g., heaving, slumping, embankment failures) • Walking/cycling pathway destabilization • Impacts to stormwater management infrastructure, water mains, underground utilities	• Rail bed/embankment destabilization • Slow orders, reduced train speed

Climate factor		Impacts on urban roads, bridges, sidewalks and supporting infrastructure (stormwater management, signals, electricity)	Impacts on urban rail infrastructure, operations and supporting infrastructure (stormwater management, signals, electricity)
Changing water levels/patterns of lake and sea ice	Ice-jam flooding	• Seasonal flooding of roadways • Utility disruption (e.g., power loss) • Overloading of stormwater management infrastructure • Bridge scour	• Seasonal flooding of railways (water-adjacent rails) • Embankment erosion/washout • Tunnel flooding (below-grade transit systems)
	Rising sea levels (coastal)	• Roadway, sidewalk, and bike path erosion/washout/inundation • Bridge scour	• Railway erosion/inundation/washout • Bridge scour
	Storm surges during extreme weather events	• Storm-surge flooding (inundation of coastal roads, bridges, highways, bike paths, and sidewalks) • Overloading of stormwater management infrastructure	• Storm-surge flooding (inundation of coastal railways) • Embankment erosion/washout • Overloading of stormwater management infrastructure
Wind	Increasing average daily wind speed/ more frequent extreme wind events	• Increased maintenance on tall structures (e.g., power lines and signals) • Malfunction and damage to traffic control signals • Unsafe working conditions due to flying debris • Blocked culverts (e.g., trees and debris) • Closure of/damage to bridges • Roadway, sidewalk, and bike path obstruction caused by debris (e.g., fallen power lines, trees, branches) • Utility and communication disruption due to loss of power • Damage to elevated walkways/ bike paths • Reduced cycling activity during high winds	• Railcar blow-over due to high-speed cross-winds • Utility disruption (e.g., power loss) • Obstruction and increased maintenance due to falling debris (e.g., fallen power lines, trees, branches) • Damage to overhead wires and signalization equipment
Wildfire	More frequent wildfire events	• Inaccessible/congested community access and evacuation points	• No examples found in the literature

6.0 CLIMATE CHANGE ADAPTATION PRACTICES FOR URBAN TRANSPORTATION

Reducing the vulnerability of Canadian urban areas to a changing climate and extreme weather requires effective governance and collaboration within and between governments, transportation agencies, and other municipal sectors. In Canada, federal, provincial and territorial policy frameworks and funding programs can support municipal adaptation efforts, while both public and private transportation agencies are responsible for providing safe and efficient services in the face of more variable weather and climate conditions.

Sharing knowledge about resilient infrastructure and operational practices is also critical. At the municipal level, there are a number of networks for climate adaptation knowledge-sharing, including ICLEI Canada (Local Governments for Sustainability). ICLEI Canada's Building Adaptive and Resilient Communities (BARC) initiative (Box 2) is an interactive web-based tool designed to help local governments identify and adopt climate adaptation strategies. Member municipalities receive one-on-one staff support for using the tool (ICLEI, 2010), and transportation is a key aspect of this program.

BUILDING ADAPTIVE AND RESILIENT COMMUNITIES (BARC) INITIATIVE

BARC operates through a five-step "milestone" process:

- ***Initiate***, in which stakeholders are identified and council resolutions made to address adaptation;
- ***Research***, which involves determination of likely climate changes and risk assessment;
- ***Plan***, in which adaptation objectives, actions, and budgeting are undertaken;
- ***Implementation***, in which actions are put into motion and political support is solidified; and
- ***Monitor/Review***, in which the effectiveness of action is determined, successes are communicated, and revisions are made (ICLEI, 2010).

Adaptation strategies can be placed into the following five categories according to their style of intervention, as per the Intergovernmental Panel on Climate Change (2014).

DISASTER RISK-MANAGEMENT STRATEGIES

These strategies are familiar to municipalities, and have helped many cities successfully reduce the impacts of severe weather events in the past (e.g., Halifax and Hurricane Juan, Slave Lake and wildfire). Examples include changing emergency-management procedures in light of experienced or expected climate-related impacts, and assessing organizational risk through programming and software applications; and others. Calgary and Toronto have recent experience with climate-related disaster response, as both cities experienced severe weather events in the summer of 2013 (Davison and Powers, 2013). Examples include updating flood-, fire-, tsunami-, and hurricane-preparedness plans, and updating floodplain maps.

SPATIAL AND LAND-USE ADAPTATION

This category of strategies includes changing procedures for land-use control and infrastructure design in certain areas to take into consideration past or expected climate impacts. Low-impact roadway designs include standards that aim to reduce total runoff and runoff rates, and natural methods to mitigate runoff (National Cooperative Highway Research Program, 2006), such as mandating the use of permeable materials (Credit Valley Conservation Authority, 2014). These are also relevant for active transportation – for instance, the North American City Transportation Officials (NACTO) guidelines for sidewalk and bikeway design recognize the importance of low-impact considerations for stormwater management. This includes increasing the permeability of construction materials (simultaneously reducing long-term infrastructure maintenance costs) to deal with excessive runoff (NACTO, 2012).

Another example includes zoning amendments or changes to construction requirements based on floodplain mapping, avoiding routing transportation through vulnerable areas, or requiring that infrastructure be elevated above a certain point (AMEC Inc., 2011). Municipalities increasingly recognize that by considering land-use and transportation at the same time, vulnerability to changing environmental conditions may be reduced (Larrivée, 2010).

STRUCTURAL AND PHYSICAL ADAPTATIONS

Perhaps the most tangible adaptation category, these strategies include engineering-based solutions to enhance the physical resiliency of urban transportation networks. To adapt to more frequent and intense rainfall events, practitioners may widen road culverts, shoulders, and ditches to improve stormwater management and sheet flow, and construct deeper gravel wells under roads and rails (Savonis et al., 2008). Flood risks due to sea level rise and storm surge can be mitigated by constructing dykes and employing other flood-management techniques around low-lying urban areas to protect roads and highways (AMEC Inc., 2011; Mills, 2016).

To adapt to changing temperatures, municipalities may employ alternative, more heat- and rut-resistant pavement materials, as well as rut-resistant pavement designs (i.e. thinner surfaces) (Andrey and Mills, 2003; United States Federal Highway Administration, 2015). For example, the Ontario Ministry of Transportation's "SuperPave" system is a materials selection system that uses local weather-station data and pavement-performance data to dictate appropriate heat- and rutting-resistant asphalt mixes for provincial highways and some municipalities in Ontario (Ontario Ministry of Transportation, 2013) (see Chapter 6). The City of Toronto has also installed cooling fans for traffic signals, and intelligent transportation system (ITS) infrastructure, to reduce risks from heat (City of Toronto, 2011).

For transportation infrastructure built on warming permafrost in northern cities, adaptation strategies include mechanical stabilization of embankments and the removal of permafrost before construction; however these methods are extremely costly (Cheng, 2005; United States Arctic Research Commission Task Force, 2003). Snow sheds, air ducts, and thermosyphons can also protect roads and rail lines from warming temperatures (Reimchen et al., 2009). Dawson City has installed light-coloured pavement on the city's main street to increase the reflectivity and reduce the impact of higher temperatures on permafrost (Walsh et al., 2009).

Other structural/physical adaptations include:

- Installing backup power infrastructure for overhead electricity (i.e. for trolleybuses, streetcars) and signals (McLeod and Stevanovic-Briatico, 2014).
- Elevating roadways and rail lines in flood-prone areas (AMEC Inc., 2011; Koatse and Rietveld, 2012).
- Undertaking comprehensive "flood-proofing" of transit corridors, in which culverts are replaced and flood sensors are installed on rail infrastructure (Transportation and the Environment Task Force, 2014).
- Waterproofing circuit breaker houses and other underground facilities that provide power to subways (McLeod and Stevanovic-Briatico, 2014).

- Performing regular maintenance of stormwater management systems, especially culverts, to maintain capacity, and designing drainage systems to direct runoff away from the roadbed (rather than parallel with the roadway), therefore avoiding erosion of the roadbed and exposure of utilities (City of Toronto, 2014).
- Maintaining positive cross-slope to facilitate the flow of water from road surfaces, and increasing culvert/ditch capacities (United States Federal Highway Administration, 2015).
- Sealing and/or elevating where appropriate street-level vents and manholes, protecting underground pump rooms, circuit breaker houses and other underground facilities that provide power to subway systems (McLeod and Stevanovic-Briatico, 2014).
- Elevating portions of vulnerable roads, sidewalks and bicycle paths above projected sea-level or flood lines (Schwartz, 2011).

INSTITUTIONAL ADAPTATION

Institutional adaptation refers to the adoption of policies targeting climate change. This includes changes to transportation agencies' service delivery, and approaches to infrastructure maintenance. For instance, on rail lines experiencing buckling, service or speed reductions might be implemented at least in the short term to ensure safety (Savonis et al., 2008). This category also includes:

- Innovative financing measures available to municipalities for adaptation, such as:
    - "Green" bonds (debt instruments used to raise private capital for projects with specific environmental purposes, including urban transit and active transportation);
    - Local tax rebates or incentives for green roofs and other stormwater management infrastructure and practices, which may produce benefits for transportation in terms of reduced runoff; and,
    - Intergovernmental grants targeted for resilient transportation infrastructure (Harford et al., 2015).
- Organizational practices identified through the PIEVC (Public Infrastructure Engineering Vulnerability Committee) climate change vulnerability assessment protocol. For example, recommendations from a PIEVC assessment of impacts related to higher temperatures and increased precipitation on roads and associated structures in Sudbury included the following:
    - More closely monitoring hydraulic data for culverts, as well as key pavement performance indicators (e.g., freeze-thaw cycles, average and extreme temperatures) annually;
    - Changing pavement mixtures to better withstand heat (i.e. SuperPave);
    - Performing sensitivity analyses on the slope stability of high-risk embankments; and,
    - Improving tree coverage on low-speed roads to reduce the urban heat island effect (Engineers Canada, 2014).
- Organizational planning, financial and risk management practices. One example is the work undertaken by TransLink to integrate climate risk into decision-making processes, which is a responsibility of their Chief Financial Officer (see Case Study 5).
- Intelligent Transportation Systems (ITS). These are becoming more prevalent, and have potential adaptive applications in urban centres. ITS technologies can help municipalities "adaptively manage" traffic flow, infrastructure maintenance practices, and investment patterns through the collection of data on operations, structural integrity of infrastructure, and other variables, including

climate data. Research suggests municipalities can optimize their winter road maintenance operations and save money with the assistance of real-time information (Fu et al., 2009). An example is the use of Roadway Information Systems in some Canadian cities, which provide real-time road condition and usage information for municipalities (Clean Air Partnership, 2012).

- Ice-reduction practices. Research suggests that "anti-icing, pre-wet salting with plowing and sanding all reduce accident occurrence" (Andrey et al., 2013) during icy road conditions. To avoid or resolve environmental issues related to increased salt use for icy roads, municipalities in Ontario have employed alternative, lower-impact melt solutions (i.e. beet juice, cheese brine) (Clean Air Partnership, 2012).

SOCIAL ADAPTATIONS

These adaptations include strategies designed to leverage social networks to increase awareness and response time during extreme events. For instance, many municipalities now use social media to help communicate travel advisories and alerts for road and active transportation infrastructure conditions (e.g., flooding) and public transit service delays during extreme weather events (Mims, 2010; White et al., 2009). Table 2 provides an overview of adaptation practices identified in this chapter.

The section to follow presents five case studies describing specific transportation adaptation approaches in Canadian cities, including discussion of where and how adaptations have been applied, benefits, costs, tradeoffs, and lessons-learned.

Table 2: Examples of adaptation practices for urban transportation (citations appear in Section 6.0).

	Climate hazards and impacts	Adaptations for roads, bridges, and associated infrastructure (including signals, stormwater management)	Adaptations for urban rail infrastructure and operations
Precipitation	Extreme precipitation; flooding; higher annual rainfall volumes	• Updating zoning by-laws to require low-impact construction standards (e.g., permeable pavements) • Expanding stormwater management capacity (e.g., widening culverts, shoulders and ditches); constructing deeper gravel wells underlying road beds to improve sub-drainage • Requiring the elevation/ relocation of roadways away from flood lines • Sealing street-level vents and manholes • Protecting underground pump rooms • Installing back-up power sources for traffic signals • Improving drainage and maintenance practices and materials (e.g., porous/ permeable materials) • Building dykes or other flood-management infrastructure • Conducting vulnerability assessments, updating emergency preparedness planning and revising floodplain mapping • Monitoring hydraulic data/ pavement performance metrics for pavement performance • Increasing inspection frequency for culverts and bridges	• Requiring track elevation above flood-lines • Constructing deeper gravel wells under rail beds to improve permeability and sub-drainage; installing pumping systems for tunnels • Waterproofing street-level vents, circuit breakers, pump houses and other underground facilities that provide power to subways • Conducting vulnerability assessments, updating emergency preparedness planning and revising floodplain maps • Using advisories and updates from transit dispatch centres for urban rail users • "Flood-proofing" transit corridors (e.g., installing flood sensors on locomotives, undertaking culvert replacement/upgrades)
	Greater proportion of freezing rain in winter precipitation	• Improving salt management practices to control snow and ice (e.g., using lower-impact materials, adjusting the timing and mixture of applications and/or snow plowing) • Considering climate risks during infrastructure renewal • Improving real-time monitoring of road conditions	• Installing back-up power for overhead electricity and signals, key maintenance and fleet facilities • Issuing service change advisories in advance of closures/delays (i.e., through social media)

	Climate hazards and impacts	Adaptations for roads, bridges, and associated infrastructure (including signals, stormwater management)	Adaptations for urban rail infrastructure and operations
Temperature	Increased freeze-thaw cycles	• Monitoring of freeze-thaw cycles, traffic levels, and rehabilitation requirements to inform budgetary changes	• No examples found in the literature
	Extreme heat (thermal expansion of bridges, pavement degradation, rail buckling, etc.)	• Using heat-resistant pavement materials • Installing cooling systems for diesel engines • Increasing frequency of bridge maintenance • Installing traffic signal cooling fans/switch heaters and using them during periods of extreme temperature • Increasing the frequency of night-time construction • Using light-coloured pavement to enhance albedo	• Installing cooling systems and track signal switch heaters • Adopting speed restrictions and service reductions to cope with rail buckling • Changing rail distressing temperatures to reduce likelihood of rail buckling • Increasing the frequency of night-time construction
	Extreme cold (electrical malfunctioning, cracking of infrastructure, etc.)	• Implementing real-time monitoring of road conditions (i.e., RWIS)	• Heating for underground tunnel infrastructure (e.g., to prevent water main breaks)
	Permafrost thaw/ degradation (ground destabilization, embankment failure, etc.)	• Installing crushed rock cooling system, or insulation/ground refrigeration system • Using light-coloured pavement to enhance albedo • Installing permafrost preservation infrastructure, such as snow sheds, thermosyphons, longitudinal air ducts, side-slope snow clearing, etc. • Relocating vulnerable roadways • Revising winter road weight/ speed limits	• Increasing frequency of rail bridge maintenance/inspection • Using social media networks to issue service advisories/ alerts • Reinforcing embankments • Installing permafrost preservation infrastructure, such as snow sheds, thermosyphons, longitudinal air ducts, etc. • Clearing side-slopes on rail embankments • Revising weight/speed limits for trains passing over weakened areas
Changing water levels / patterns of lake and sea ice	Flooding due to changing patterns of lake and sea ice/ water levels (ice-jam flooding, storm surge, sea level rise, etc.)	• Investing in dykes, sea walls, or flow-management infrastructure • Improving stormwater management capacity (e.g., widening culverts, shoulders, ditches); constructing deeper gravel wells underlying road beds to improve sub-drainage • Using permeable pavements • Using social media networks to issue travel advisories/alerts • Elevating roadways, sidewalks, and bike paths above flood lines (or relocating if a recurring issue)	• Investing in dykes, sea walls or flow-management infrastructure • Using social media networks to issue travel and service advisories/alerts

	Climate hazards and impacts	Adaptations for roads, bridges, and associated infrastructure (including signals, stormwater management)	Adaptations for urban rail infrastructure and operations
Wind	Damage to signals, signs and associated equipment	• Improving structural design of tall infrastructure for more turbulent wind conditions (i.e. bridges, traffic signals) • Installing back-up power sources for traffic, pedestrian, and cycling signals	• Improving structural design of tall infrastructure for more turbulent wind conditions (e.g., bridges, rail signals) • Installing backup power sources for rail signals
Wildfires	Inaccessible/ congested community access points	• Updating emergency response/ contingency planning for evacuation • Developing a business continuity plan for extreme weather events so that critical services can be maintained	• No examples found in the literature
General		• Incorporating climate change considerations into financial risk management practices, asset management, and service delivery • Issuing "green bonds" to raise capital for environmentally-sound infrastructure projects • Implementing local tax rebates/incentives for private landowners to improve stormwater management • Accessing intergovernmental grants targeted for resilient transportation infrastructure • Improving redundancy within and between modes to enhance resiliency • Purchasing transit vehicles (buses and trains) better able to withstand adverse weather conditions • Increasing land-use mix to reduce the number and length of vehicle trips (reducing road wear and tear) • Establishing a schedule for assessing infrastructure usage/condition/ climate interactions • Conducting emergency drills across municipal departments (ensure personnel and equipment are prepared) • Undertaking/updating floodplain mapping to identify vulnerable community infrastructure and assets • Amending/updating zoning by-laws and standards to account for sea level rise, require set-backs, etc.	

CASE STUDY 1

CASE STUDY 1: AN INNOVATIVE TOOL TO ASSESS CLIMATE RISKS AT THE CITY OF TORONTO

Adaptation is critical for large cities' transportation networks, given the social and economic importance of safe and fluid mobility. The City of Toronto anticipates that climate-related risks to its transportation system will significantly increase in coming decades (City of Toronto, 2008). Decisions made today regarding capital investments, program delivery, and relationships with key partners will be important to ensure that the City improves its resilience to climate change.

This reasoning underpinned the City of Toronto's decision to develop a Climate Change Adaptation Strategy. Toronto's City Council provided the necessary political capital, resulting in a report and program entitled "Ahead of the Storm: Preparing Toronto for Climate Change" (City of Toronto, 2008). This was a screening-level, cross-cutting exercise in assessing organizational vulnerability to climate change, including a review of international best-practices and tools. Transportation was a key focus area of a multi-stakeholder working group, featuring participants both internal and external to the City of Toronto. The resulting report recommended the development of a practical tool for assessing vulnerabilities and risks to the city's transportation infrastructure and operations, in the context of both extreme weather events and slow-onset climate change. The City selected a consultant consortium to create a Climate Change Risk Assessment Tool and Process (CCRAT). This software application enables service and infrastructure providers to identify and prioritize key environmental and climate change-related risks, as well as to assess the benefits of various mitigation and adaptation actions.

The City of Toronto's Transportation Services Division (TSD) demonstrated leadership and helped develop and apply the CCRAT pilot. The outputs included an overview document, an assessment process, a software tool, and a user manual. This was a ground breaking exercise for the City. Prior to this undertaking, the City did not know if it was feasible to deploy a risk assessment tool with available resources and knowledge.

In 2011, TSD applied CCRAT to evaluate the vulnerability and resilience of 90 high-priority assets and critical services to seven extreme weather events. Through a series of 15 half-day workshops, 14 risk assessors, looked at 1650 impact scenarios for the time periods 2010-2020 and 2040-2050. The team developed "risk scenarios" (combinations of extreme weather events and impacts) based on identified causes and vulnerabilities. Impacts could be multiple or cascading (i.e., up to "four-order impacts"), for example, economic impacts resulting from transportation delays caused by road or lane closures during extreme weather events. TSD's risk assessors also identified more than 60 existing initiatives that enhance adaptive capacity, as well as 100 short- and long-term adaptation actions. Examples of ongoing initiatives include:

- Adding heating and cooling fans in traffic signal controllers;
- Developing guidelines for the construction of "green" streets;
- Coordinating efforts to enhance the urban canopy to reduce heat-island effects; and,
- Using combination ploughing and salting vehicles to better react to freezing rain conditions (City of Toronto Environment Office, 2011).

The development and application of the CCRAT was an opportunity for the municipality to demonstrate its due diligence to citizens, and build organizational awareness. Another key output was the city's Climate Change Risk Management Policy, which established an institutional foundation for adaptation.

Practitioners involved with the CCRAT consider it a success. The use of both top-down (city-driven) and bottom-up (grassroots) approaches where appropriate was considered particularly beneficial, as was the establishment of a well-defined work program in which roles and responsibilities of all stakeholders were clearly delineated. Each functional group within TSD developed clearly-defined expectations for the services they deliver and the infrastructure they maintain. The appointment of specially-trained risk assessors for each group was viewed as integral to organizational cohesion. Selecting a chief risk assessor as a

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project manager – a team leader experienced with environmental management systems, risk assessment, and a comprehensive understanding of the organizational structure – was also crucial.

A number of lessons were learned:

- Practitioners suggest the CCRAT would have been more effective if interdependencies and “synergistic risks” between the public and private sectors (such as energy, communication, insurance and finance) were identified prior to its undertaking. Engagement and collaboration with these sectors reduces the risk of economic disruption to the community and enables opportunities for more adaptive and resilient infrastructure.

- Another potential shortcoming was that “residual risk” (the degree of risk that remains once an adaptation has been implemented) was not assessed for each proposed adaptation action as part of this phase. Residual-risk analysis and cost-benefit analysis can be useful and important mechanisms to assist municipal managers in prioritizing adaptation actions.

- Practitioners also identified challenges in effectively communicating the severity of climate change to the public. The Royal Academy of Engineering (2011) notes the importance of consulting users of the assets and services regarding potential new service levels in addition to the amount tax payers would agree to pay for a particular level of service. A significant challenge for both industry and politicians is how to best communicate to the public the limits of resilience and the need to modify demand for infrastructure.

Overall, the CCRAT has helped Toronto set clearer organizational goals on the issue of climate adaptation, and allows TSD to manage its assets and services in accordance with City Council’s priorities of customer-service excellence and cost reduction in a transparent and fully-accountable manner. Critically, many of the adaptations CCRAT identified do not require major increases in capital or operating budgets. For instance, enhancing inventory databases, adopting environmental management systems, providing training, and improving coordination to reflect “best-management” principles and increase both adaptive capacity and organizational efficiency, involve little or no extra cost for the municipality. This is an example of “low-regret” adaptation. Focus is now shifting to ambitious, long-term actions which require additional investment. The summer of 2014 saw a high level of council support for these actions (such as a new culvert management system, approved for $350,000 to inventory all culverts less than 3m (in width) in the city’s road network. In sum, the City of Toronto considers the CCRAT useful for both private and public sectors to assess their vulnerabilities to climate change and develop an adaptation path to resiliency.

Written with input from Nazzareno Capano (Transportation Services Division, City of Toronto) and Vesna Stevanovic-Briatico (Transportation Services Division, City of Toronto).

CASE STUDY 2

CASE STUDY 2: CLIMATE CHANGE ADAPTATION AT THE CITY OF MONCTON

Many Maritime cities have already begun experiencing climate-related impacts. In Moncton, New Brunswick, the frequency of flooding from extreme storm events and changing tidal patterns has increased over the past decade (City of Moncton, 2013). Moncton is located at the nexus of the Petitcodiac River and the Bay of Fundy, a region that experiences one of the largest tidal ranges in the world. Coastal and inland flooding, as well as erosion, pose significant risks to transportation infrastructure. The region is also expected to experience gradual sea-level rise and significant precipitation and temperature increases by mid-century (AMEC Inc., 2011).

From 2010 to 2012, communities in the Greater Moncton Area participated in the Atlantic portion of the Regional Adaptation Collaborative (RAC) program. This cost-sharing initiative with provincial and federal governments was designed to identify climate-change threats, vulnerabilities, and adaptation tools useful in addressing erosion, coastal and inland flooding, infrastructure design, and groundwater management. Transportation was an area of focus within this initiative, largely in recognition of historical problems in the region with transportation and sanitary-sewer infrastructure located below flood thresholds.

Specific recommendations for the City of Moncton emerging from the RAC exercise, were to:

- Develop new arterial roads to avoid low-lying areas and the floodplain of the Petitcodiac and its tributaries;
- Elevate new roadway and bridge infrastructure to ensure access to essential services during extreme weather events;
- Flood-proofing major roads at vulnerable elevations to minimize flood-related damage and ensure rapid system recovery; and,
- Mandate higher flood elevations in future transportation planning decisions (AMEC Inc., 2011). A minimum elevation of 10.5 metres was proposed to reflect the 100-year flood event line the region is likely to experience by 2100, informed by floodplain mapping.

In response, the City of Moncton produced a corporate Climate Change Adaptation and Flood Management Strategy in 2013, and has since introduced a series of policy changes. For example, the City:

- Changed its zoning bylaw to set minimum floor elevations for habitable space at 10.5 m;
- Will elevate new roadways and bridges, where feasible to do so, above the 10.5-m threshold;
- Developed extensive evacuation plans for existing vulnerable roadways in the event of a major storm surge event; and
- Offers a $500 rebate on the installation of an approved backwater valve, as part of an incentive program for local property owners.

Building on these initiatives, Moncton has developed a Regional Sustainable Transportation Master Plan that will help the City assess the vulnerability of all transportation modes in the network using detailed mobility and flood scenarios. The results will help the City prioritize network improvements and street upgrades. The models and flood scenarios allow for provincial officials to identify their interests (provincial infrastructure in the community) likely to be affected under future conditions. Recommendations will be made to council regarding infrastructure requiring upgrading or abandonment, with budgetary requirements made clear.

The effectiveness and timeliness of Moncton's adaptation planning, policies, and practices can be attributed to the support for adaptation from all levels of government. At the municipal level, the Climate Change Action Committee, composed of staff from most City departments, reports to council annually. Practitioners agree that it has done an excellent job of creating accountability on climate adaptation both within and between departments. Developing an integrated approach both within the municipality and with provincial and federal partners has proven invaluable.

Written with input from Elaine Aucoin (Environmental Management and Planning, City of Moncton) and Stephane Thibodeau (Engineering and Environmental Services, City of Moncton).

CASE STUDY 3

CASE STUDY 3: TRANSPORTATION ADAPTATIONS TO CLIMATE CHANGE IN THE CITY OF WHITEHORSE, YUKON

Whitehorse is a significant regional transportation hub, with rail, marine, and air transportation all playing important roles in the city's history. The city relies heavily on the Alaska Highway for external connectivity and on the automobile for urban mobility, although public transit services are also available. The city's climate is relatively warm (compared to other northern communities) and semi-arid due to its location within the range shadow of coastal mountains. In recent years, however, Whitehorse has experienced highly variable precipitation, including many winters with above-average snowfall. Climate changes of this nature pose a number of risks to the city's transportation network. Projected increases in wildfires and the intensity, duration, and frequency of storm events (and associated flood and drainage concerns) create indirect risks to road traffic. Local officials identify highway obstructions and washouts during extreme weather events as a key concern, as they can prevent the delivery of food and other essential goods. Other impacts to urban transportation include increased frequency of freeze-thaw cycles; strain on the road-maintenance budget in high-snowfall winters; and, greater stress on culverts due to increased summer and winter precipitation.

To address these concerns, the City of Whitehorse participated in the development of the community-based Whitehorse Climate Change Adaptation Plan in 2011 (Hennessey and Streicker, 2011). This project involved a diversity of community stakeholders. While not legally-binding (the document is policy-relevant, but not policy-determinate) the plan has helped to "mainstream" the changing climate into municipal decision-making processes, meaning that climate data and projections are incorporated into investment and planning decisions. The plan's broad goals include enhancing transit's mode share, intensifying development, and increasing the region's share of agricultural production through food security planning (including the production of more food in nearby greenhouses, reducing reliance on imports). Suggested adaptations for urban transportation include:

- Establishing annual budgets aimed at managing climate change concerns, including planning for increased snow removal requirements;
- Expanding the use of road monitoring stations;
- Conducting exploratory feasibility studies of automatic road de-icing techniques; and
- Increasing the porosity of road surfaces to improve re-charge following precipitation.

These adaptations include both "low-regret" and "no-regret" measures. For example, when road improvements are required due to the lifecycle or condition of the infrastructure, the Plan suggests that the City upgrade water and sewer systems to accommodate larger stormwater flows. This requires only a modest marginal-cost increase to the budget for the project. At the same time, this strategy means only those roads nearing the end of their lifespan or in very poor repair will be adapted in the near-term, given that the cost of replacing usable infrastructure with larger drainage capacity is prohibitive. For practical purposes, this is an adaptation approach that must be implemented in a piecemeal manner. A "no-regret" adaptation on the operational side involves proactive early-spring inspections of drainage to identify frozen storm drains and reduce flood risks.

Flooding is also a concern on Whitehorse's residential roadways, with some older subdivisions having experienced localized issues as a result of outdated drainage systems. As a result, stormwater infrastructure in new subdivisions is now designed with higher volume thresholds. Additionally, Whitehorse is using transportation redundancy as an adaptation solution on a small scale; subdivisions are no longer permitted to be built with only one road-access point in case of washouts, flooding, and wildfire hazards.

Written with input from John Streicker (City ofWhitehorse) and Jocelyn Beatty (University of Waterloo).

CASE STUDY 4

CASE STUDY 4: ROAD SAFETY AND CLIMATE CHANGE IN PRINCE GEORGE

Prince George, located in the interior of British Columbia, is home to approximately 76,000 people. The city has a wide range of transportation modes, including rail, inland marine, and urban transit. While the city's transportation network faces a number of risks from climate change, warmer winter temperatures are likely to have the greatest impact, primarily due to increased freeze-thaw cycles, rain-on-snow events, and freezing rain. Flooding on the Nechako (due to ice jams) and Fraser (due to freshet) rivers is another key concern. Prince George developed a number of transportation-specific climate change adaptations in 2012, in recognition of the risks flooding poses to roads, active transportation infrastructure, and rail facilities. This was done in the context of a larger community adaptation plan.

A steering committee composed of local practitioners and experts from academia (to balance local needs with best practices) identified 23 forward-looking adaptation actions, in the areas of infrastructure, operations, emergency response and safety, and financing.

Through the process, the city also identified a number of ongoing initiatives that fall under the umbrella of climate adaptation. These included snow and ice control, salt management, road elevation, and dyke construction. For instance, following an ice-jam flood of an industrial area in 2008, the city elevated a roadway to a 1-in-200 year flood level, and constructed a 3.3 km dyke to protect local rail infrastructure (Picketts, 2012). The committee's final recommendations for immediate action included changes to winter road maintenance, improvements to road safety, and climate-sensitive design considerations (Picketts, 2012). The city listed transportation as its highest-priority area in the city for continued action (Picketts et al., 2013).

Prince George is now focused on implementing action items in key areas, with promising early returns. The city has begun to aggregate climate data and procedural information to better inform road maintenance decision-making, including data on vehicle and climate interactions. With respect to road design and stormwater management, a number of new permeable materials have been proposed for testing. Next steps include:

- Continuing partnerships with universities and the provincial government;
- Encouraging climate assessments for all new infrastructure projects;
- Incorporating climate data into decision-making criteria;
- Maintaining dialogue with the transportation industry; and,
- Encouraging the exchange of information among city staff members (Picketts, 2012).

The transportation component was considered successful by practitioners, given the high degree of public interest in mobility issues; the practical nature of the solutions that were explored; and the clear potential for significant cost savings. However, one drawback to the project's focus on winter road safety was relatively little attention was paid to active and public modes of transportation (Picketts, 2014). Feedback from practitioners involved in the implementation process highlighted four key areas for attention, with specific relevance to adaptation in mid-sized, northern communities:

1. Building and maintaining local knowledge and capacity for decision-making around climate adaptation;
2. "Mainstreaming" or normalizing adaptation into the plans, priorities, and professional practices of local officials;
3. Focusing on tangible projects around which the community can rally and easily identify results; and;
4. Linking adaptation actions to costs and priorities through clear communication to both politicians and members of the public (Picketts, 2014).

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This case study demonstrates how communities can successfully incorporate rigorous climate analysis into vulnerability assessments, shifting discussion from a general recognition of risks to the identification of explicit actions (Picketts, 2013). Achieving greater teamwork and the adoption of common goals within the municipal organization were also considered critical to sustaining the momentum this initiative has generated.[1]

Written with input from Dr. Ian Picketts (University of Northern British Columbia).

1 An academic journal article summarizing the transportation work in Prince George is in the final stages of review for inclusion in a forthcoming issue of *Regional Environmental Change*.

CASE STUDY 5

CASE STUDY 5: ACCOUNTING FOR CLIMATE CHANGE RISKS AT TRANSLINK

TransLink is metropolitan Vancouver's regional transportation authority, with a system of assets and services that incorporates bus, commuter rail, cycling and walking paths, and roads. This network provides about 1.2 million trips per day.

The organization considers managing climate change risks important to service delivery and infrastructure maintenance/development, particularly given that it builds infrastructure to last 100 years. Projected population growth in the region is expected to compound these risks – Metro Vancouver is expected to grow by one million people over the next 30 years, placing greater demand on the region's transportation system.

TransLink began considering climate change impacts in 2010 and conducted a climate change vulnerability assessment of its assets in 2012 in support of its Asset Management Plan. Through this process, the organization identified the following key climate change risks to its services:

- Sea level rise, that could:
  - Flood assets now within "expanded" floodplains,
  - Reduce clearance under bridges
  - Impair operations of the SeaBus (ferry) terminal.
- Increased precipitation that could cause temporary flooding of TransLink's assets, such as bus loops, tunnels, transit stations and trolley electricity conversion ("rectifier") stations.
- Warmer temperatures, and more frequent and severe heat waves, that could affect passenger health and comfort on parts of the fleet without air-conditioning.

TransLink has also ensured that its Finance department and accountants play a core role in its adaptation efforts. The Chief Financial Officer (CFO) is responsible for seeing that climate change risks are considered in TransLink's decision-making process. TransLink considers this structure effective as it embeds climate change throughout the organization, with links to risk management, strategic sourcing, capital planning and review processes, and reporting.

Written by Kathy Palko, adapted from Chartered Professional Accountants Canada (2015) Adaptation Case Study #2[2]

2 CPA (2015) Adaptation Case Study #2: TransLink Sector: Transportation. Retrieved from: https://www.cpacanada.ca/en/business-and-accounting-resources/other-general-business-topics/sustainability/publications/translink-climate-change-case-study-2

7.0 INTERDEPENDENCIES WITH OTHER URBAN SECTORS

Urban transportation networks depend on other infrastructure and utilities, (including electricity and telecommunications) to move large volumes of people and goods efficiently. The interdependencies among these systems, the economy, and society are explored in this section.

Electricity is one key interdependency. Growing dependence on the electrical grid for urban mobility (particularly for LRT and commuter rail systems, but also for automobiles and infrastructure) can create multi-sectoral vulnerability when extreme weather events disrupt the supply and distribution of electrical power. Ensuring traffic signals remain operational during and immediately following extreme weather is another concern.

Intelligent Transportation Systems (ITS) applications, used heavily for public transit and traffic management, also depend upon telecommunications infrastructure that can be affected by extreme weather (Revi et al., 2014). Without adequate coordination, interactions between water mains and underground public transit systems can potentially disrupt both sectors. This is the case under both slow-onset climate change and during extreme weather events. For example, pipes can freeze and rupture during freeze-thaw cycles or extreme cold conditions damaging the water distribution infrastructure and disrupting the underground public transit systems. This has been experienced by the Toronto Transit Commission's subway system in recent winters (McLeod and Stevanovic-Briatico, 2014).

The ability of transportation agencies to reduce damages associated with severe weather is therefore affected by how other municipal divisions and utility providers (e.g., telecommunications and energy supply) integrate climate change considerations into their own planning and service delivery. If one sector is at risk, so are many others. For example, if floods or heat waves disrupt the energy supply, all other services can be affected, causing failures to cascade. If road traffic is not flowing freely, the efficiency of an entire city may be reduced.

In locations where infrastructure is at risk of being compromised or failing as a result of climate impacts, Business Continuity Planning becomes important. This refers to planning that ensures services are not compromised by extreme or unforeseen events. Planning in advance how the workforce can be more effectively deployed in emergency and post-emergency situations is critical, particularly since climate change is anticipated to bring more frequent extreme weather events. Practitioners interviewed for this chapter indicated that interdepartmental coordination can be improved if decision-makers work closely with city engineers and technical advisory committees on climate adaptation strategies for transportation infrastructure and operations.

For example, the City of Toronto's Transportation Services Division (TSD) has collaborated with a number of other municipal sectors and agencies on climate change adaptation and preparedness activities. Table 3 identifies these ongoing initiatives. Interdependencies between sectors identified by TSD include power outages caused by extreme heat, wind, and freezing rain, as well as impacts on the traffic control system and communication infrastructure. Transportation practitioners suggest that a climate change risk assessment of the electricity sector would help to identify areas of the City most vulnerable under various climate scenarios. This information would inform the implementation and spatial deployment of adaptation measures, such as uninterruptable power supply technology to traffic control signals.

Disruptions to road and transit networks will also affect the ability of staff to travel to work, resulting in personnel shortages and, ultimately, impacts to municipal service delivery. Business continuity planning for extreme weather events can address these issues, by planning for alternative work arrangements, periodic training, trial-testing of emergency management procedures, and maintaining an emergency contact information database for staff (held by a supervisor and accessible at all times).

Table 3: Example of internal and external collaboration in adaptive planning for climate change and urban transportation at the City of Toronto.

Partnership	Coordinated action
Toronto and Region Conservation Authority (TRCA)	Flood Warning System: • TRCA provides flood warnings to TSD's Road Emergency Services Communications Unit (RESCU) for the Don Valley Parkway expressway and Bayview Extension. This real time monitoring, using cameras and communication protocol, helps TSD implement road closures and manage traffic. • TSD meets regularly with TRCA staff to review flood-response protocols and real time response to events, and to establish a more comprehensive response to flooding. Environmental assessment: • TRCA is undertaking an in-house environmental assessment and collaborating with TSD to identify risks and possible mitigation actions to enhance current control measures for flooding along the Don Valley parkway and Bayview Avenue (Don Valley Corridor).
Consultation with City of Toronto Energy and Environment Office; Toronto Transit Commission and Engineering and Construction Services; and other agencies, boards, commissions, and divisions	Climate Change Risk Assessment (CCRA) (See Case study 1): • This tool identifies and assesses risks due to climate change, including the effect of climate change on the delivery of services, management of infrastructure and protection of the natural environment. • The CCRA enables service and infrastructure providers to identify and prioritize key climate change impacts and risks, and assess benefits of various risk mitigation or adaptive actions.
Toronto Transit Commission (TTC)	Examples of some collaborative initiatives include: a) TSD developed a harmonized process for implementing concrete bus bays and stops; asphalt pavement surfaces at bus stops generally exhibit severe distortion (e.g., rutting) due to bus loads and extreme heat conditions; b) Installation of concrete bus pads on the roadway as part of resurfacing projects. These are typically applied only in situations where the existing asphalt surface is shoving or rutting moderately (>25mm) or more; c) TSD identified and prioritized 100 traffic signal locations for the installation of uninterruptable power supply (UPS) devices, including signals at railroads, major intersections and expressway ramp terminals. A pilot program was initiated to outfit 12 high-priority locations. d) A second-phase review is underway to identify UPS needs for critical intersections located on emergency routes; and e) TSD established contracted services for mobile diesel and gas trucks; third party fuel cards are available when supply of fuel is affected during extreme weather events.

Outside of municipal departments, there is also a need to fully engage urban civil society and provide information about the importance of adaptation to the public (Larrivée, 2010). Practitioners suggest that public engagement on adaptation tends to yield conversations about climate mitigation (the reduction of carbon emissions). The task of municipal agencies is to emphasize the importance of both policies in tandem to maximize social value from infrastructure investments. Public engagement is also necessary to prepare society to function – access jobs, health care and other activities – when transportation systems or infrastructure systems are performing at lower levels.

8.0 GAPS AND BARRIERS

Practitioners suggest that without buy-in from the executive to operational levels on the severity of climate change risks, adaptation planning efforts often fail to be fully implemented. In some instances, practitioners have found success by communicating the importance of avoiding more significant costs in future through proactive investments. Cost-benefit analysis can also support adaptation decisions, by helping practitioners prioritize infrastructure-upgrade investments and demonstrate the value of actions taken to reduce future vulnerability (Feltmate and Thistlethwaite, 2012). As more cities achieve and communicate long-term cost savings and economic competitiveness from adaptation measures, barriers to the widespread introduction of these measures are reduced.

Coordinating actions among multiple levels of government, agencies, and sectors is another challenge to adaptive decision-making. For example, municipal governments facing flood risks must coordinate emergency-response with other orders of government, in addition to dealing with the challenges of flood prevention and physical protection (Chiwizer and Tarlock, 2013).

9.0 CONCLUSION

This chapter has demonstrated many ways in which urban transportation networks are vulnerable to climate change and extreme weather, and has identified efforts that Canadian cities are making to manage these risks. While municipalities have historically taken adaptive action in the wake of catastrophes, the case studies identified in this chapter suggest that increasingly, municipalities and their partners are working to proactively adapt both infrastructure and operations in advance of climate impacts. Case studies in the chapter provide examples of Canadian urban regions engaging in vulnerability assessments, structural and physical improvements, and organizational change to improve their resiliency to a rapidly changing transportation environment. The literature identifies additional adaptation approaches that may be applied by transportation professionals in Canada, as appropriate. It is clear that solutions will involve an appropriate mix of proactive and reactive adaptations.

This chapter has also highlighted the importance of redundancy (of both routes and modes) to enhance resiliency, as well as the importance of "low-regret" adaptation strategies in building support for adaptation efforts within governments and communities. The high up-front costs of many adaptation strategies (particularly structural solutions) may be a deterrent, and the complex fiscal and operational environments of modern cities pose obstacles to adaptation. Therefore, it is increasingly important for transportation practitioners to work in collaboration with other municipal sectors towards common adaptation goals. With strong cooperative efforts, Canada's multimodal urban transportation networks can more successfully meet the challenges of a changing climate.

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