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CHAPTER 6: ONTARIO

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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).

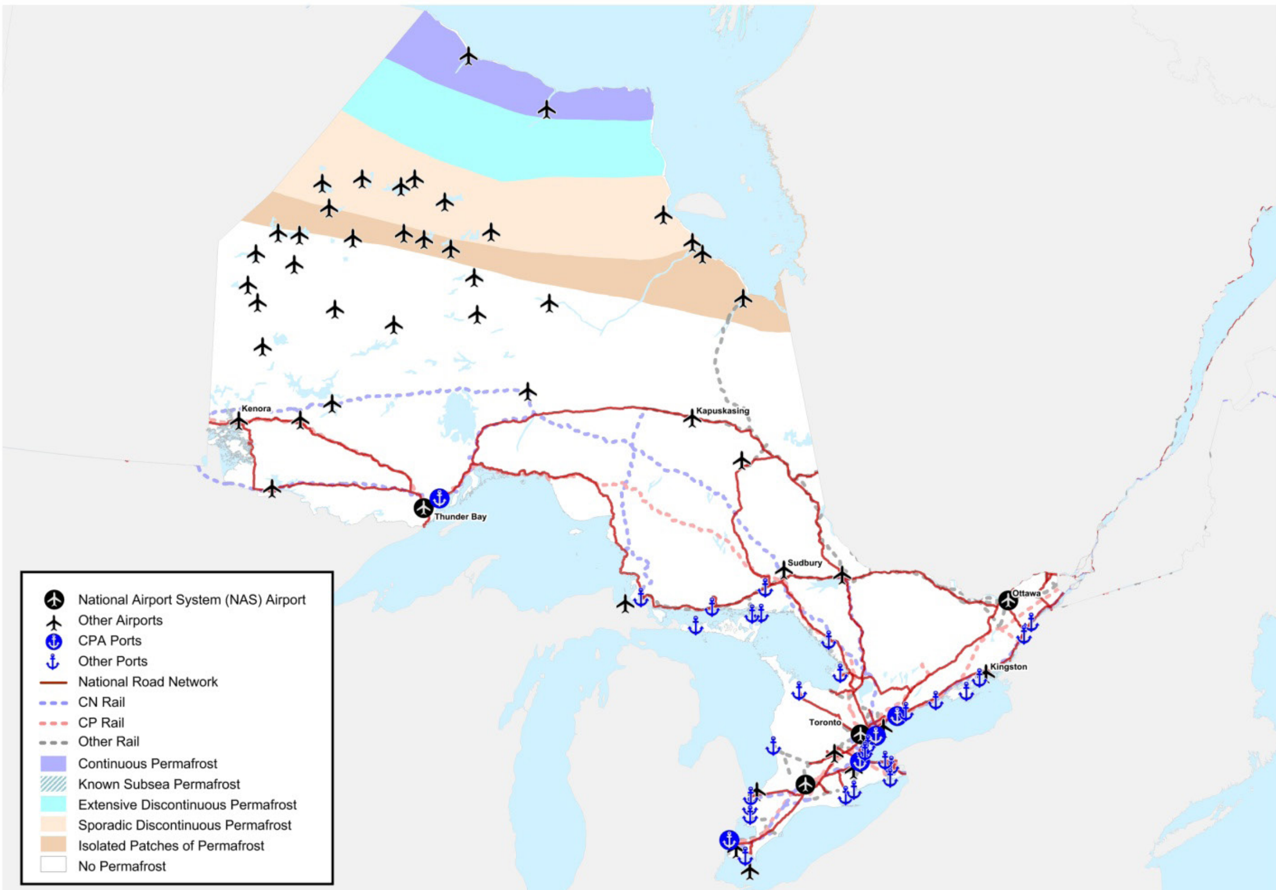
Central Ontario contains the majority of the province's 40 operational mines, representing significant economic opportunity (Ontario Ministry of Northern Development and Mines, 2013). Thunder Bay is a key transportation hub for air, rail, and marine-shipping traffic, while Sudbury's economic base includes 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.



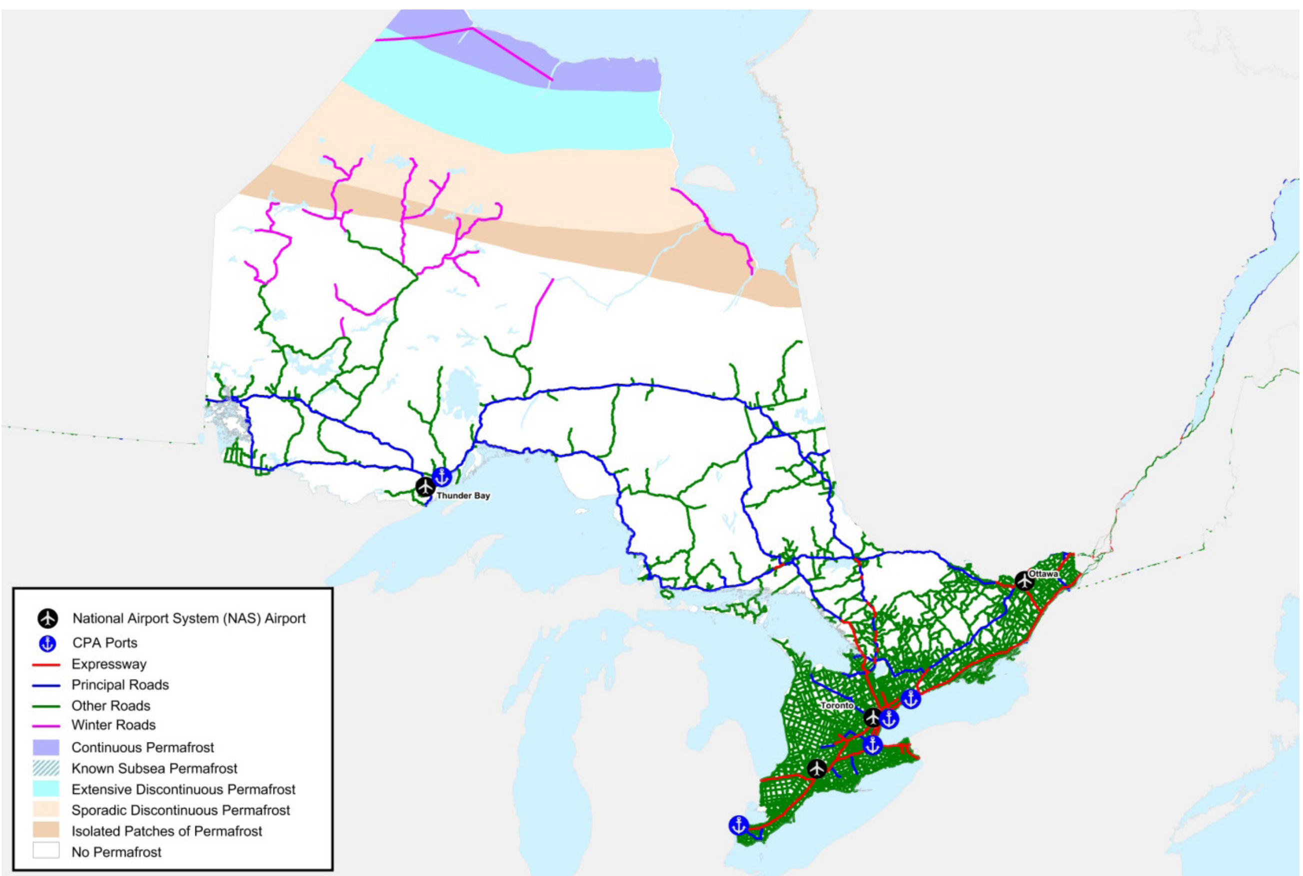
2.1 ROAD TRANSPORTATION

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

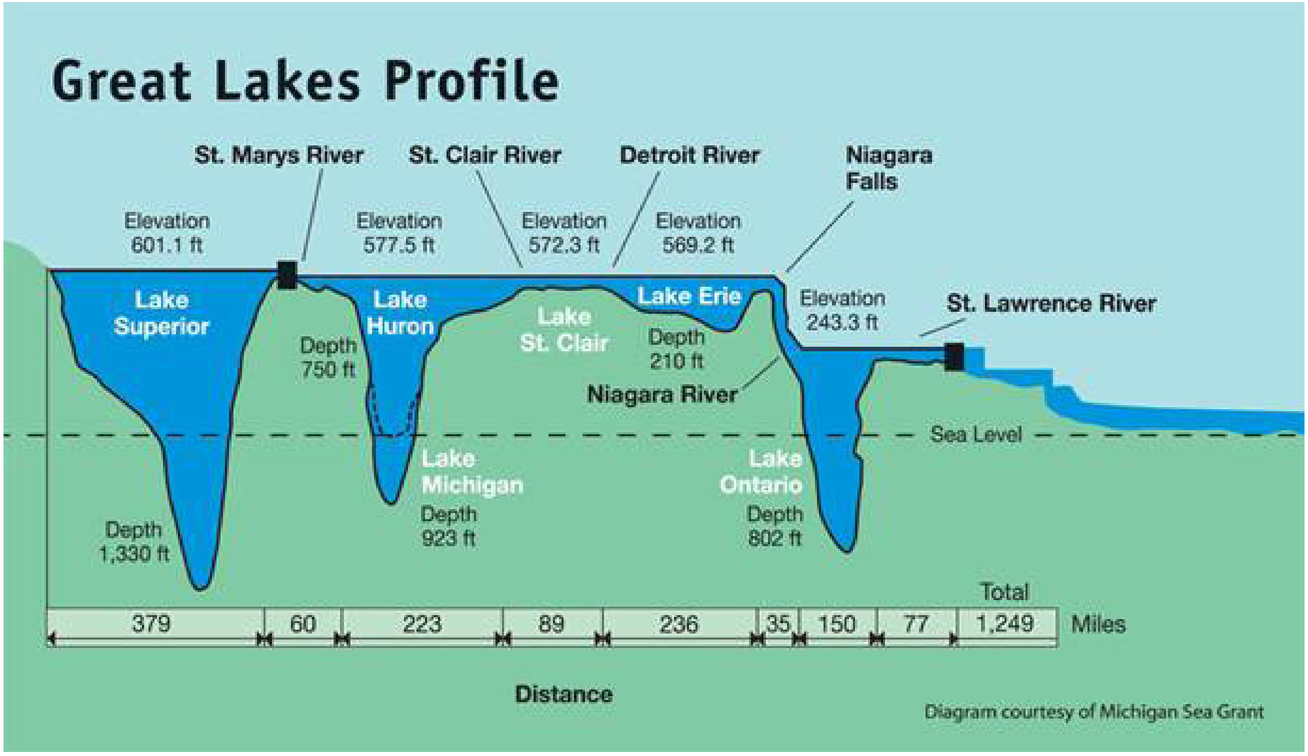
Throughout Ontario, mean annual surface air temperatures have increased by a range of approximately 1.0-1.5°C from 1948 to 2012, while central and northern regions experienced slightly larger increases (Vincent et al., 2015). The greatest warming has occurred in winter. Reflecting these warmer winters, 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)

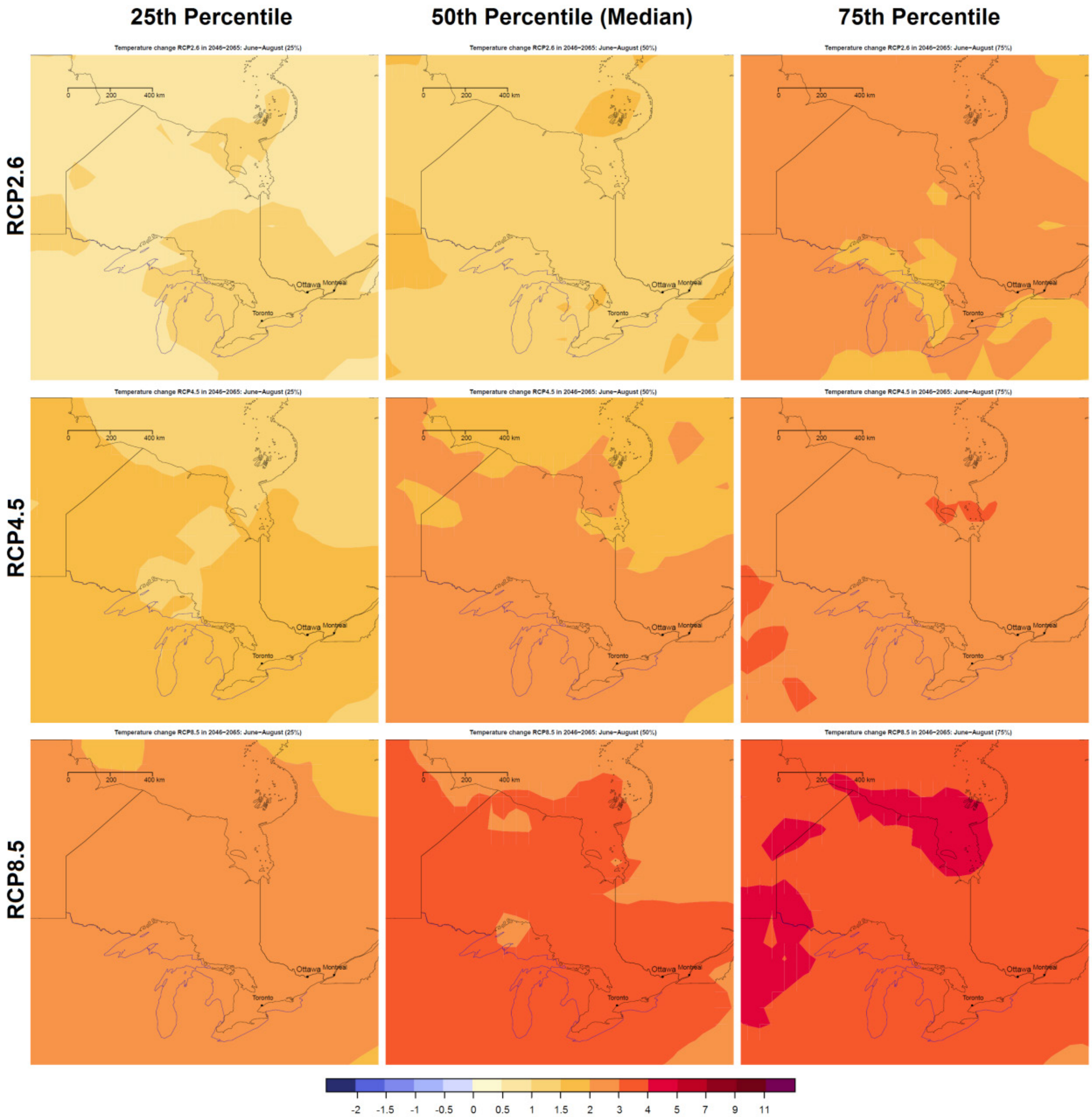
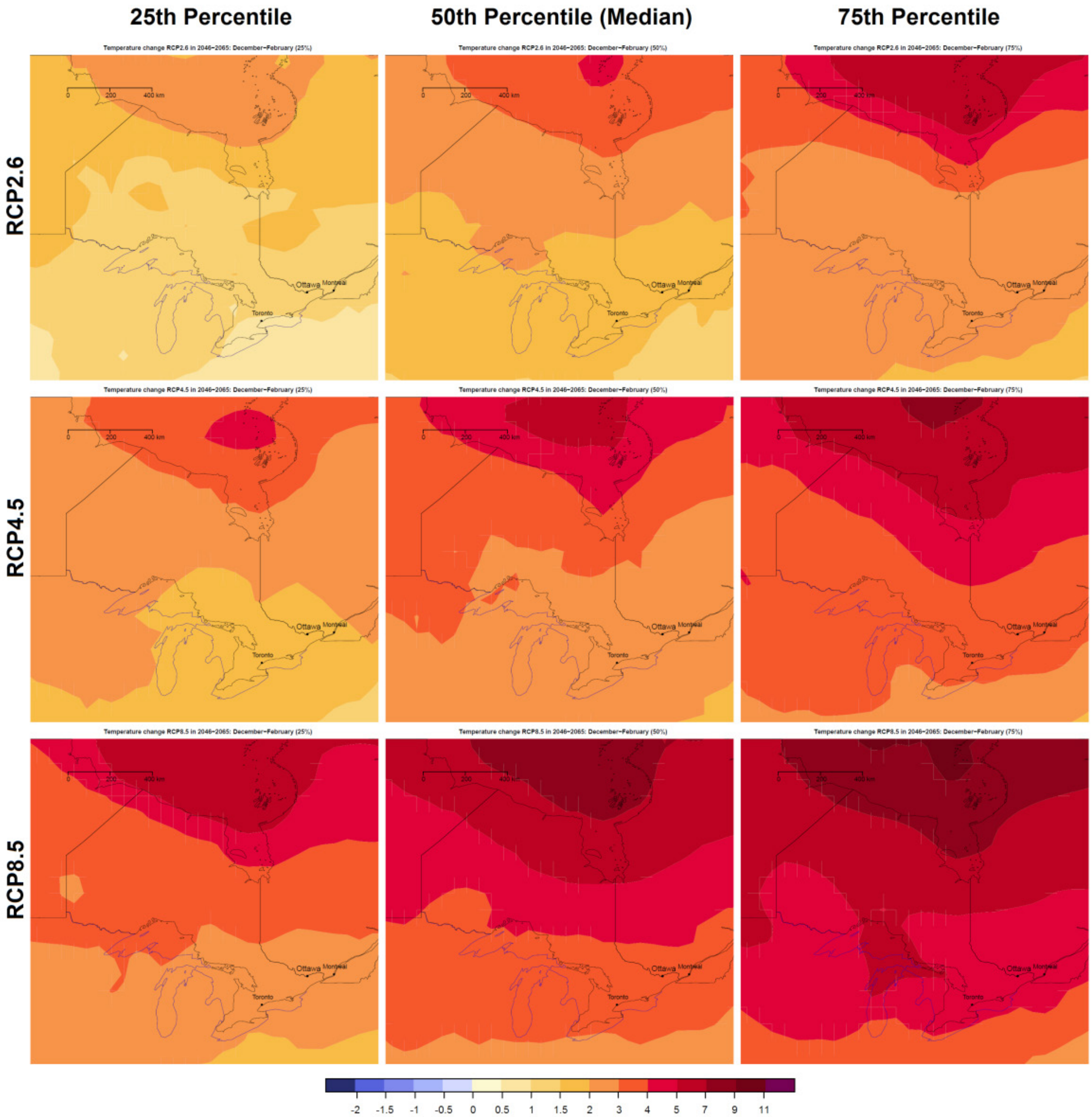


Figure 5b: Temperature changes for Ontario in winter (December, January, and February) under RCP 2.5 (low-emissions scenario), RCP 4.5 (intermediate-emissions scenario), and RCP 8.5 (high-emissions scenario) for 2046-2065, as compared to baseline years 1986-2005. (Source: Environment and Climate Change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

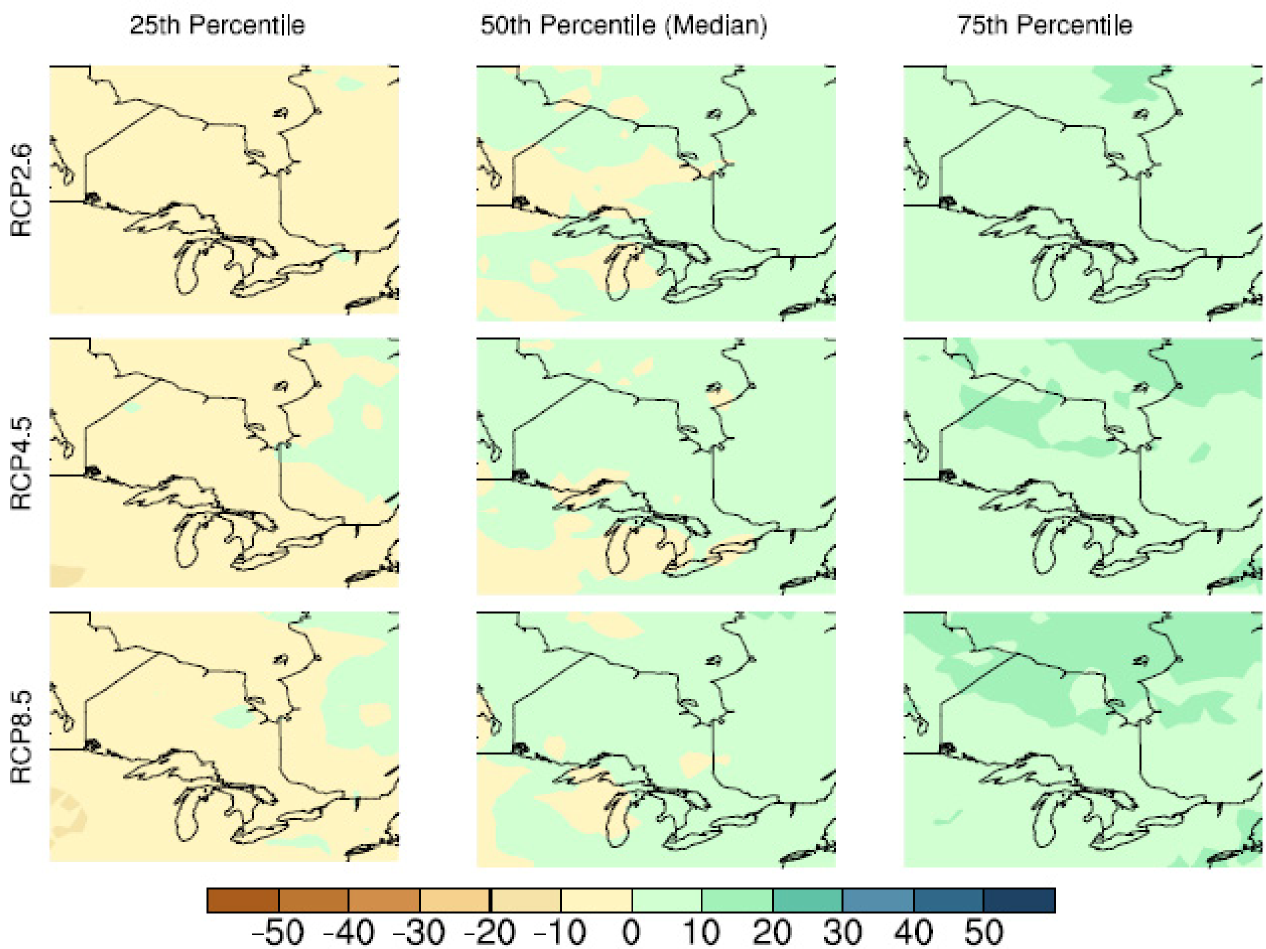
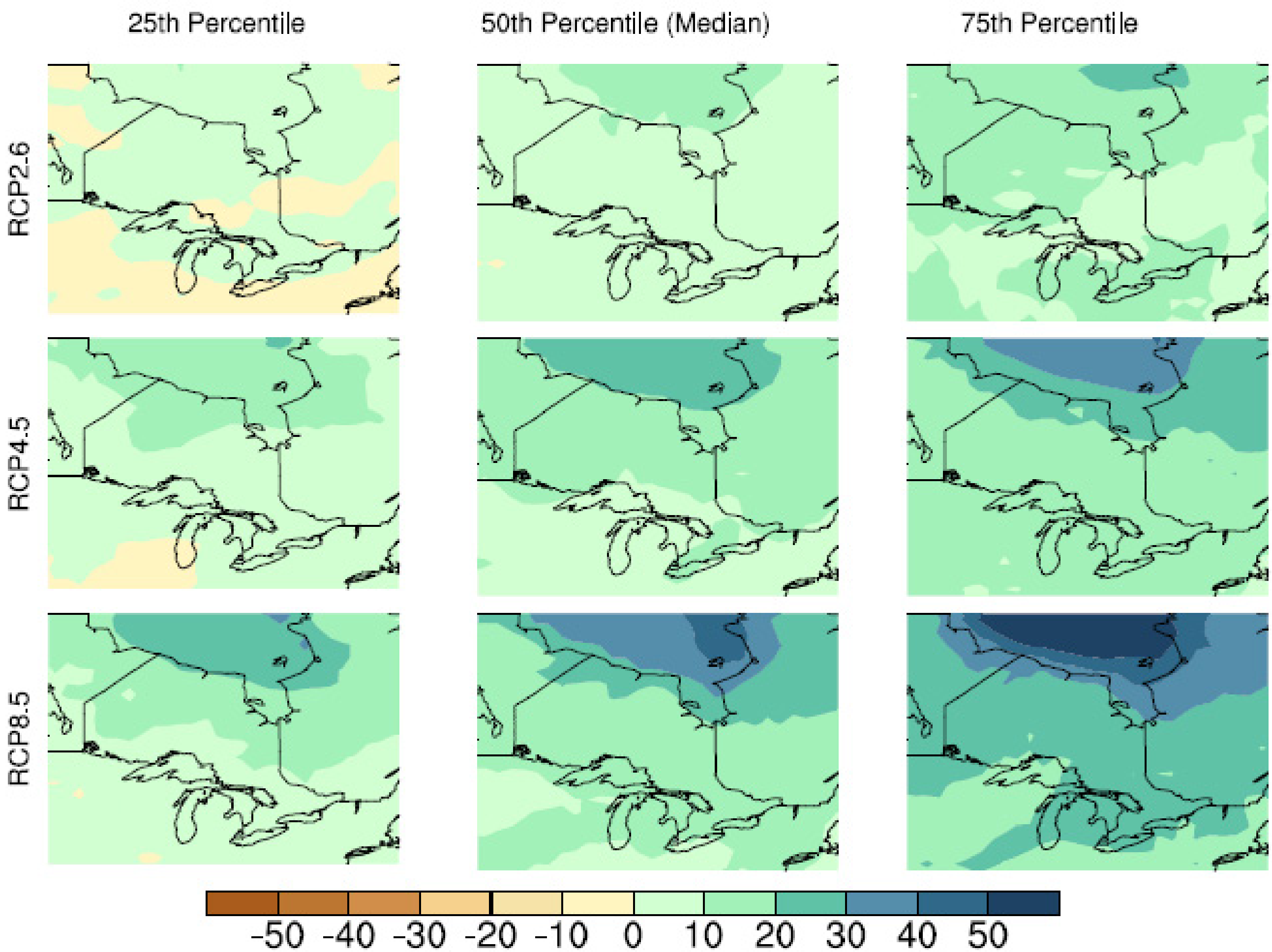


Figure 6b: Precipitation changes for Ontario in winter (December - February) under RCP 2.5 (low-emissions scenario), RCP 4.5 (intermediate-emissions scenario), and RCP 8.5 (high-emissions scenario) for 2046-2065, compared to baseline years 1986-2005. (Source: Environment and Climate Change Canada)



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.

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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