



5 • Prairies

CHAPTER 5: THE PRAIRIES

LEAD AUTHORS:

AL PHILLIPS¹
WILL TOWNS²

CONTRIBUTING AUTHORS:

PETER DZIKOWSKI (ALBERTA TRANSPORTATION),
HUGH DONOVAN (CITY OF EDMONTON),
NAOMI HAPPYCHUK (NORTHERN SUSTAINABLE PROSPERITY
INITIATIVE, UNIVERSITY OF WINNIPEG)

RECOMMENDED CITATION:

Phillips, A., and Towns, W. (2017). The Prairies. In K. Palko and D.S. Lemmen (Eds.), *Climate risks and adaptation practices for the Canadian transportation sector 2016* (pp. 105-137). Ottawa, ON: Government of Canada.

¹ Transport Institute, University of Manitoba, Winnipeg, MB
² School of Planning, University of Waterloo, Waterloo, ON and Transport Canada, Ottawa, ON

TABLE OF CONTENTS

- Key Findings 107
- 1.0 Introduction 107
 - 1.1 Geography and the physical environment 108
 - 1.2 Economy..... 109
- 2.0 Overview of transportation in the Prairies 110
 - 2.1 Road transportation 110
 - 2.1.1 Winter roads 111
 - 2.2 Rail transportation 112
 - 2.3 Aviation 112
 - 2.4 Marine transportation 112
- 3.0 Climate profile 113
 - 3.1 Past trends 113
 - 3.2 Projections 116
 - 3.3 Climate, weather and transportation in the Prairies 117
- 4.0 Road transportation..... 117
 - 4.1 Impacts on road infrastructure 117
 - 4.2 Impacts to trucking operations..... 118
 - 4.3 Adaptations for road infrastructure..... 118
 - 4.4 Adaptations for trucking operators..... 122
 - 4.5 Winter roads 122
- 5.0 Rail transportation 125
 - 5.1 Past impacts and future risks 125
 - 5.2 Rail adaptations 129
- 6.0 Aviation..... 131
 - 6.1 Past impacts and future risks 131
 - 6.2 Adaptation practices 132
- 7.0 Marine transportation 132
 - 7.1 Future climate impacts and opportunities 132
 - 7.2 Marine infrastructure and operational adaptations 133
- 8.0 Information gaps and conclusions..... 134
- References 135

KEY FINDINGS:

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

1.0 INTRODUCTION

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

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

1.1 GEOGRAPHY AND THE PHYSICAL ENVIRONMENT

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

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

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

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



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

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

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

1.2 ECONOMY

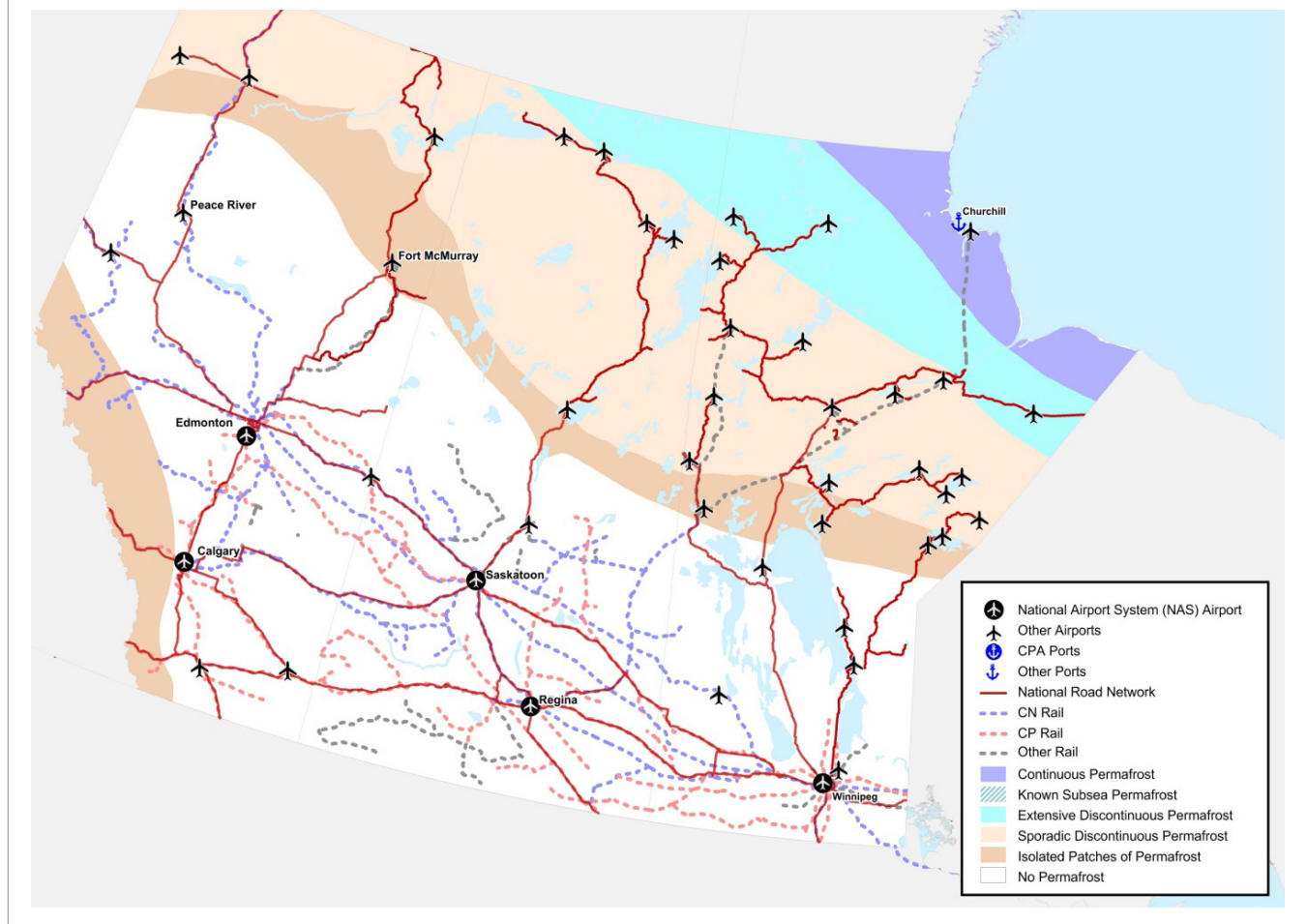
The Prairies economic strength derives from natural resource extraction. From 2010 to 2011, the gross domestic product (GDP) of the three provinces collectively rose 11.1 percent to \$429.5 billion, nearly doubling the national growth rate. By 2014, the region's contribution to Canada's GDP totaled 25.6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

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

2.0 OVERVIEW OF TRANSPORTATION IN THE PRAIRIES

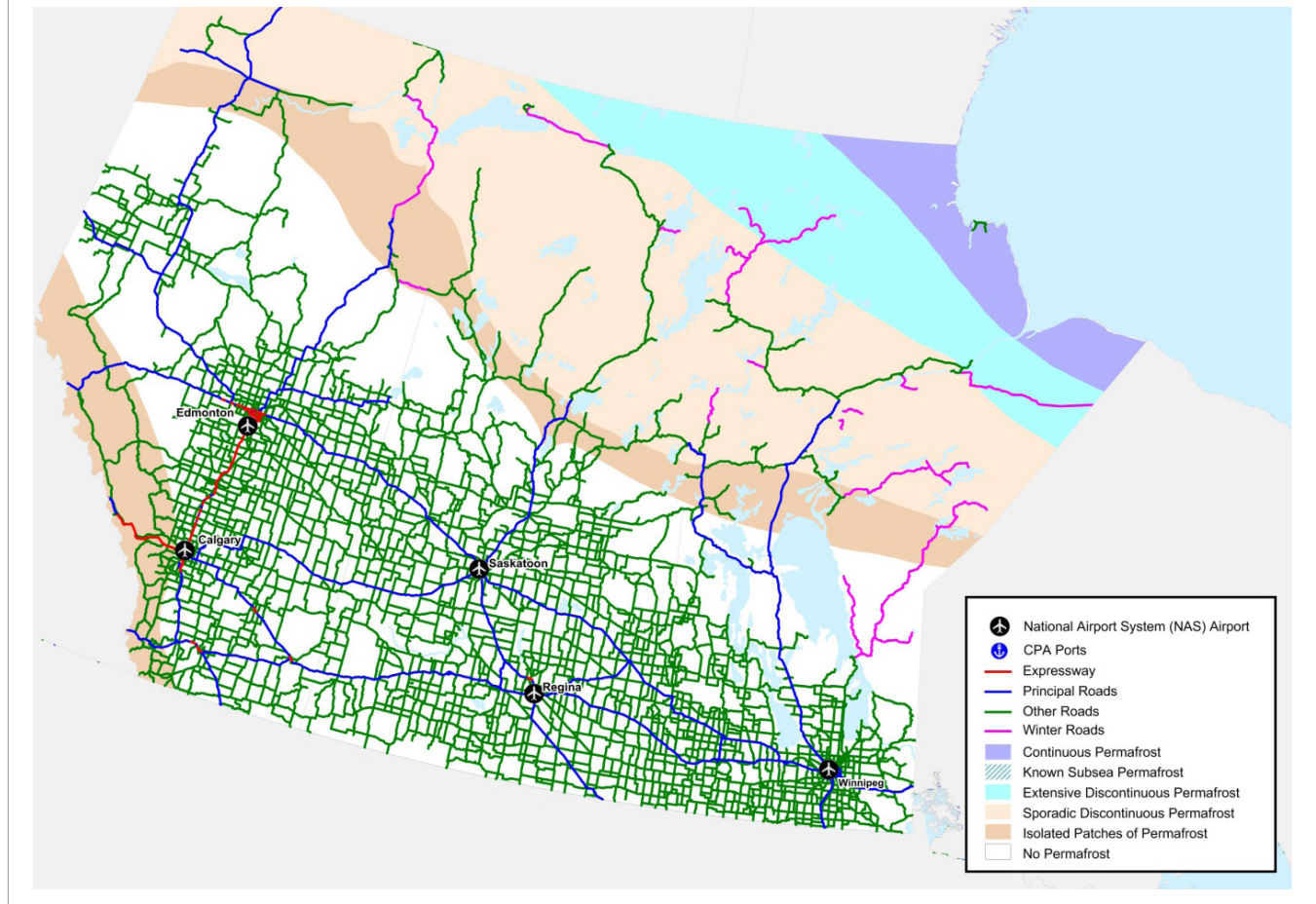
The Prairies' transportation network is extensive, with road, rail, and aviation providing options for the movement of people and freight. While the Prairies' surface transportation network supports significant marine activity in other Canadian regions, marine transportation plays a smaller role in the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

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



2.1 ROAD TRANSPORTATION

The Prairies have a relatively high number of road-km per capita due to an extensive municipal and provincial road network, and a lower population density than the national average (3.3 versus 3.7 persons per km²) (Statistics Canada, 2011). The Prairies account for 47 percent of Canada's public roads, although this drops to 26 percent if only paved roads are considered (Transport Canada, 2015). Saskatchewan accounts for almost half (48 percent) of the region's total road-km (295,100 km), Alberta ranks second with 228,600 km (37 percent of Prairie road-km), followed by Manitoba, with 91,700 km (15 percent) (Transport Canada, 2015). Figure 3 demonstrates the extent of the Prairies' road network.

Figure 3: Road infrastructure in the Prairies.

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

2.1.1 WINTER ROADS

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

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

2.2 RAIL TRANSPORTATION

Rail transportation makes a significant contribution to freight movement in the Prairies. Three Class-I railways³ (Canadian National - CN, Canadian Pacific - CP, and Burlington Northern and Santa Fe - BNSF) carry the vast majority of regional rail freight. Most tracks are located in areas without permafrost. One exception is the rail line connecting Churchill, Manitoba with supply-chain hubs to the south (Figure 2).

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

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

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

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

2.3 AVIATION

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

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

2.4 MARINE TRANSPORTATION

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

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

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

3.0 CLIMATE PROFILE

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

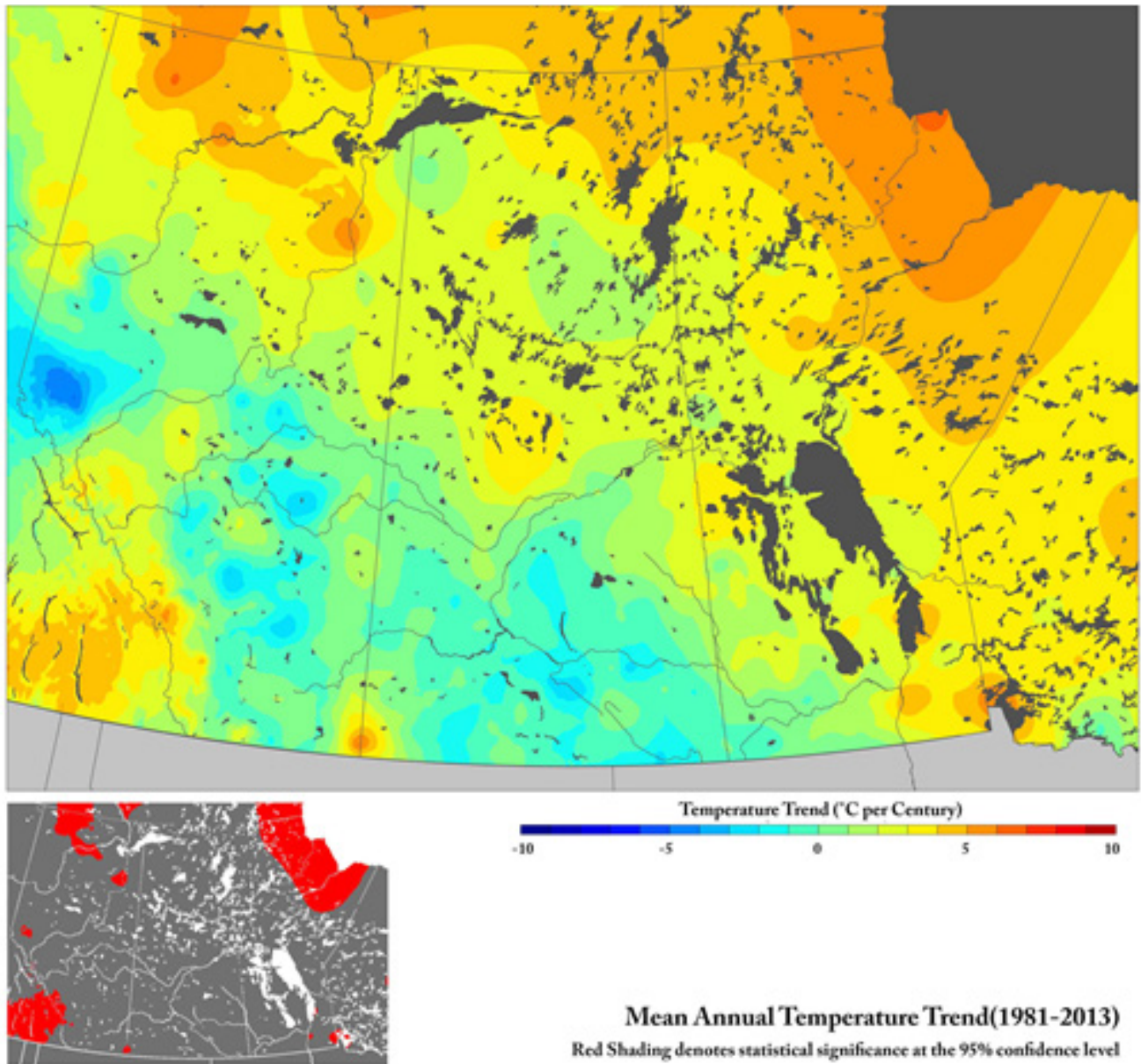
In the context of a changing climate, increasing water scarcity represents a risk to the region. Also, the Prairies are likely to lose advantages associated with cold winters, particularly as they relate to winter roads (Sauchyn and Kulshreshtha, 2008).

3.1 PAST TRENDS

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

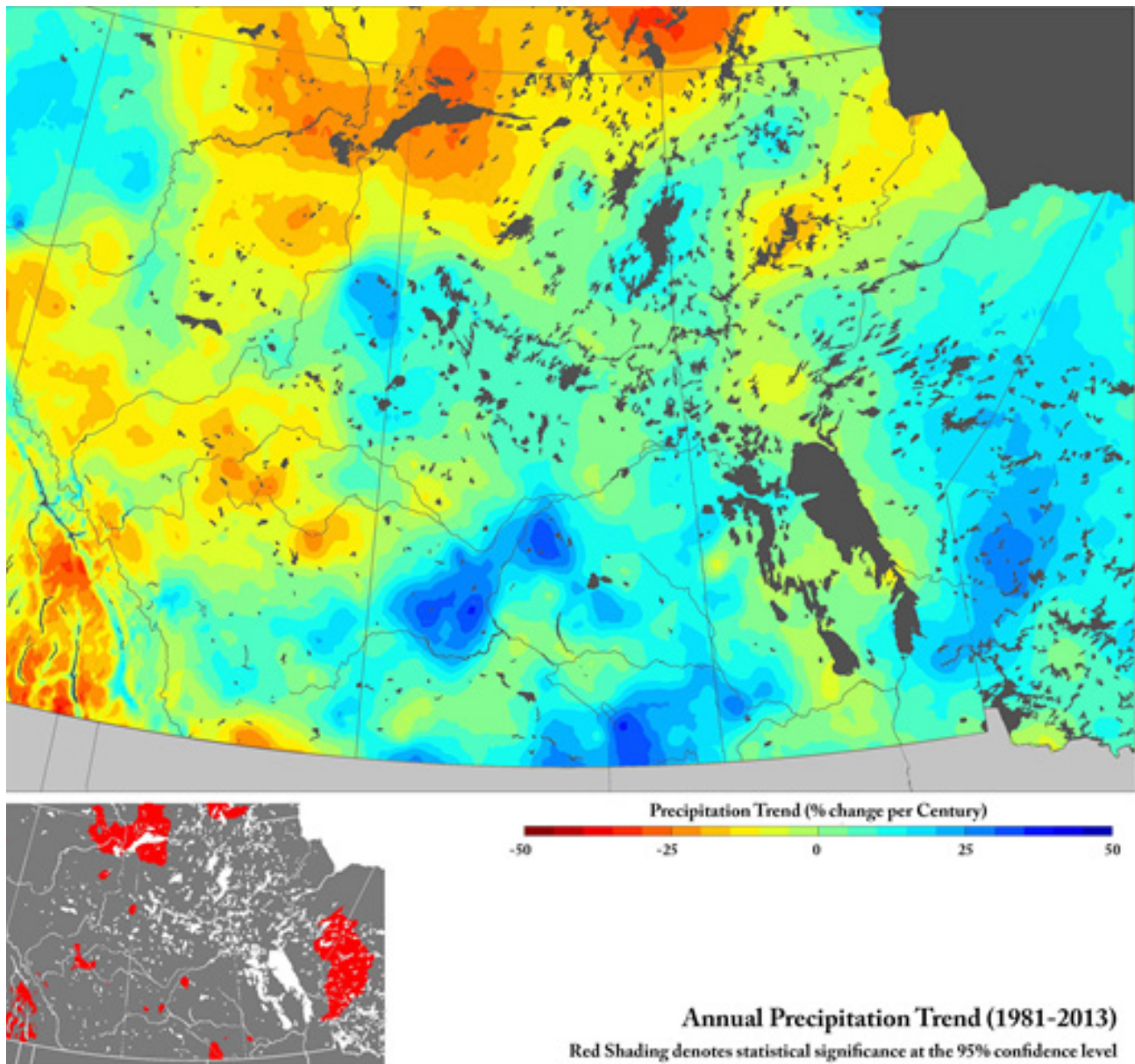
In addition to significant variability between and among years, there is also significant spatial variability across the region. In examining mean annual temperature trends, research (Danny Blair and Ryan Smith, University of Winnipeg, personal communication, 2015) demonstrates that most of the region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

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



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

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



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

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

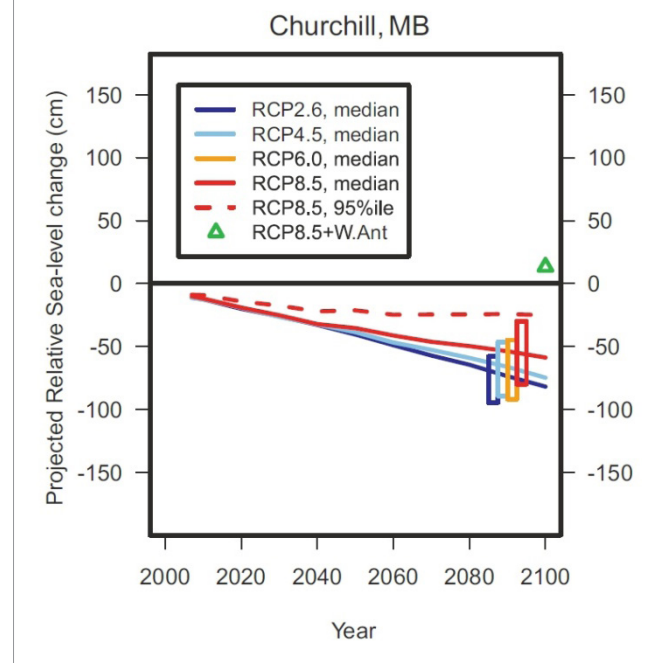
3.2 PROJECTIONS

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

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

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

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



3.3 CLIMATE, WEATHER AND TRANSPORTATION IN THE PRAIRIES

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

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

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

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

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

4.0 ROAD TRANSPORTATION

4.1 IMPACTS ON ROAD INFRASTRUCTURE

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

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

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

4.2 IMPACTS TO TRUCKING OPERATIONS

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

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

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

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

4.3 ADAPTATIONS FOR ROAD INFRASTRUCTURE

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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



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

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

CASE STUDY 2

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

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

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

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

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

Written with input from Hugh Donovan (City of Edmonton)

4.4 ADAPTATIONS FOR TRUCKING OPERATORS

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

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

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

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

4.5 WINTER ROADS

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

Shorter winter road seasons can result in significant social and economic impacts. Governments and businesses use these roads to transport important supplies such as chemicals, fuel, and other daily essentials for residents, businesses, and public utilities (CBC News, 2012a). Residents use ice roads to access urban areas and purchase supplies in bulk, reducing the household impact of high living-costs

in remote northern communities. If ice is not thick enough for transit by mid-January, a modal shift from trucks to aviation for essential goods is required, at great expense to all users (Taylor and Parry, 2014). When ice roads eventually open in mild winters, load restrictions can be applied (CBC News, 2012b). Recent winter-road experiences in Manitoba are discussed in Case Study 3.

CASE STUDY 3

CASE STUDY 3: WINTER ROADS IN MANITOBA

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

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

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

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



...

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

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

Written by Will Towns and Al Phillips

12-year
average, all
routes

5.0 RAIL TRANSPORTATION

5.1 PAST IMPACTS AND FUTURE RISKS

EXTREME PRECIPITATION

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

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

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

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



EXTREME TEMPERATURES

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

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

CASE STUDY 4

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

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

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

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

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

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

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





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

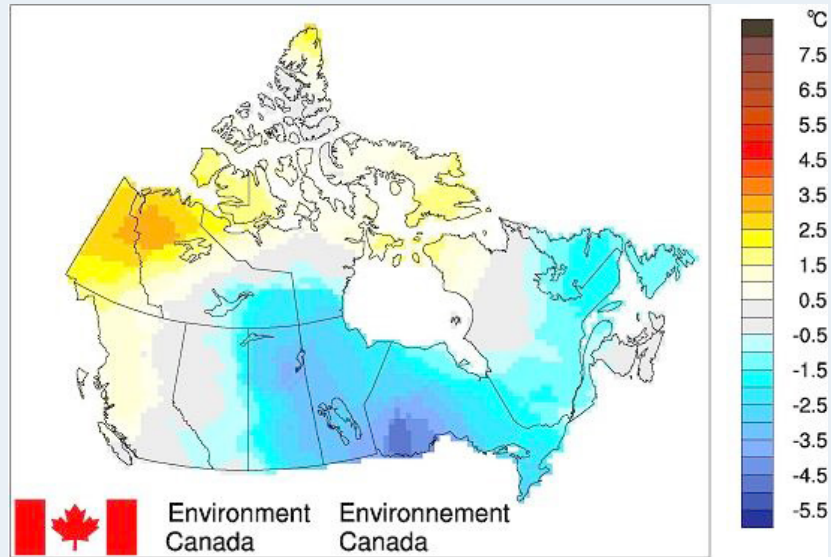


Figure 9a shows weekly rail transit times for trains going from British Columbia ports to Toronto. Two pronounced spikes in transit time are apparent. The first corresponds to a rail labour strike in 2012, while the second corresponds to the extreme cold winter of 2013-14.

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



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

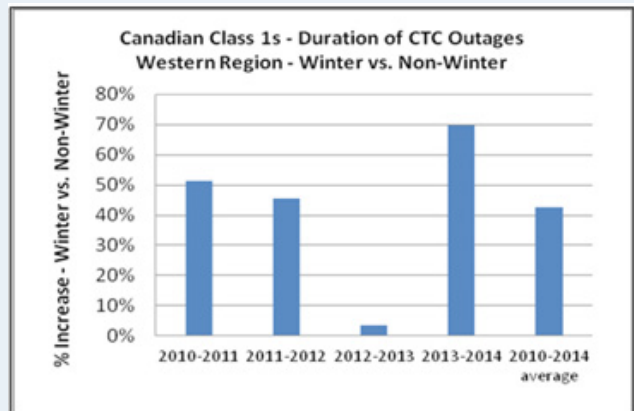


Figure 9b illustrates a critical measure related to lower train speeds, higher dwell times and more re-crews - the number of “centralized traffic control” (CTC) outages. These outages mean that normal centralized dispatch systems are down, requiring slower train movements and positioning until the system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

Written by Al Phillips

OTHER CLIMATE RISKS

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

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

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

CASE STUDY 5

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

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

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

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

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

Written by Al Phillips and Will Towns

5.2 RAIL ADAPTATIONS

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

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

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

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

CASE STUDY 6

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

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

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

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





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

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

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

Written by Al Phillips

6.0 AVIATION

6.1 PAST IMPACTS AND FUTURE RISKS

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

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

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

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

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

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

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

6.2 ADAPTATION PRACTICES

INFRASTRUCTURE

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

OPERATIONS

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

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

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

7.0 MARINE TRANSPORTATION

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

7.1 FUTURE CLIMATE IMPACTS AND OPPORTUNITIES

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

7.2 MARINE INFRASTRUCTURE AND OPERATIONAL ADAPTATIONS

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

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

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

CASE STUDY 7

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

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

1. Development and use of an **integrated supply chain model** that supports a **systematic understanding** of how decisions could affect the supply chain as a whole.
2. **Integrated governance** for transportation infrastructure supporting the North.
3. **Integrated planning and strategic investment strategy** for northern transportation infrastructure.

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

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





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

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

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

8.0 INFORMATION GAPS AND CONCLUSIONS

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

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

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

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

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

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

REFERENCES

- Addison, P., Oommmen, T., and Lautala, P. (2015). A review of past geotechnical performance of the Hudson Bay Railway embankment and its comparison to the current condition. *Proceedings of the 2015 Joint Rail Conference*.
- Amiro, B., Rawluck, C., and Wittenburg, K. (2014). *Moving toward prairie agriculture 2050 (Green paper)*. Alberta Institute of Agrologists Conference Proceedings, p. 35. Retrieved from http://www.albertaagrologists.ca/site/page_404?url=http://www.albertaagrologists.ca/files/conferences/2014%20aia%20conference/conference%20handouts/2014%20green%20paper%20final%20pdf%20for%20web.pdf
- Andrey, J., and Mills, B. (2003). Climate change and the Canadian transportation system: Vulnerabilities and adaptations. In J. Andrey and C. Knapper (Eds.), *Weather and transportation in Canada* (pp. 235-279). Publication series number 55, Department of Geography, University of Waterloo.
- Atkins, E. (2014, November 9). After harsh winter, North American railways brace for repeat performance. *The Globe and Mail*. Retrieved from <http://www.theglobeandmail.com/report-on-business/despite-rosy-forecast-north-american-railways-brace-for-harsh-winter/article21514708/>
- Atkinson, D.E., Forbes, D.L., and James, T.S. (2016). Dynamic coasts in a changing climate. In D.S. Lemmen, F.J. Warren, T.S. James, and C.S.L. Mercer Clarke (Eds.), *Canada's marine coasts in a changing climate* (pp. 27-68). Ottawa, ON: Government of Canada.
- Babaian, S. (1985). *The coal mining industry in the Crow's Nest Pass*. Edmonton, AB: Alberta Culture.
- Beaudoin, A., Lemmen, D., and Vance, R. (1997). *Paleoenvironmental records of postglacial climate change in the Prairie ecozone*. Retrieved from http://www.scirpus.ca/eman/eman_page1.htm
- Bonsal, B., Aider, R., Gachon, P., and Lapp, S. (2013). An assessment of Canadian prairie drought: Past, present, and future. *Climate Dynamics*, 41 (2), 501-516.
- Bonsal, B., Wheaton, E., Chipanshi, A., Lin, G., Sauchyn, D., and Wen, L. (2011). Drought research in Canada: A review. *Atmosphere-Ocean*, 49(4), 303-319.
- Boyle, J., Cunningham, M., and Dekens, J. (2013). *Climate change adaptation and Canadian infrastructure: A review of the literature*. Winnipeg, MB: International Institute for Sustainable Development. Retrieved from http://www.iisd.org/pdf/2013/adaptation_can_infrastructure.pdf
- Bush, E.J., Loder, J.W., James, T.S., Mortsch, L.D., and Cohen, S.J. (2014). An overview of Canada's changing climate. In F.J. Warren and D.S. Lemmen (Eds.), *Canada in a changing climate: Sector perspectives on impacts and adaptation* (pp. 23-64). Ottawa, ON: Government of Canada.
- Cash, M. (2014, April 10). Embattled railway boss fires back. *Winnipeg Free Press*. Retrieved from <http://www.winnipegfreepress.com/business/embattled-railway-boss-fires-back-254675851.html>
- CBC News. (2012a). *Manitoba ice roads threatened by mild weather*. Retrieved from <http://www.cbc.ca/news/canada/manitoba/manitoba-ice-roads-threatened-by-mild-weather-1.1291472>
- CBC News. (2012b). *Manitoba's winter roads finally open*. Retrieved from <http://www.cbc.ca/news/canada/manitoba/manitoba-s-winter-roads-finally-open-1.1274617>
- CBC News. (2015a). *Wildfires in Saskatchewan forcing evacuations, road closures*. Retrieved from <http://www.cbc.ca/news/canada/saskatchewan/wildfires-in-saskatchewan-forcing-evacuations-road-closures-1.3131340>
- CBC News. (2015b). *Airship made in Manitoba almost ready for test flight*. Retrieved from <http://www.cbc.ca/news/canada/manitoba/airship-made-in-manitoba-almost-ready-for-test-flight-1.3271827>
- City of Edmonton. (2008). *Climate change vulnerability assessment for Quesnell Bridge*. Retrieved from <http://www.pievc.ca/e/casedocs/edmonton-quesnell/Quesnell%20Bridge%20of%20Edmonton%20Refurbishment%20Alberta%20Final%20Report.pdf>
- City of Edmonton. (2011). *Quesnell Bridge and Whitemud Dr. widening – Now fully open*. Retrieved from http://www.edmonton.ca/transportation/road_projects/quesnell-bridge-and-whitemud-drive-widening-rehabilitation-project.aspx
- Dai, A. (2011). Drought under global warming: A review. *Wiley Interdisciplinary Reviews*, 2(1), 45-65.
- Duguid, T., Happychuk, N., Rempel, R., Swanson, D., Gerrard, P. (2015). *Climate risk assessment of transportation infrastructure requirements supporting the MB-NU supply chain*. Governments of Manitoba and Nunavut.
- Ebert, R. (2000). Understanding the impact of transportation on economic development. *Transportation in the new millennium: State of the art and future directions (Perspectives from Transportation Research Board standing committees)*. Washington, DC: National Research Council of the National Academies.
- Environment Canada. (2014). *Canadian top ten weather stories for 2013*. Retrieved from <http://www.ec.gc.ca/meteo-weather/default.asp?lang=En&n=5BA5EAFC-1&offset=2&toc=hide>
- Environment Canada. (2015a). *Spring and summer weather hazards*. Retrieved from <https://ec.gc.ca/meteo-weather/default.asp?lang=En&n=6C5D4990-1>
- Environment Canada. (2015b). *Climate trends and variations bulletin – Annual for 2014*. Retrieved from <https://www.ec.gc.ca/sc-cs/default.asp?lang=En&n=60AC2030-1>
- Federal-Provincial Task Force on the Future of Churchill. (January 2013). *Final Report*. Government of Canada and Manitoba Government. Retrieved from https://www.gov.mb.ca/mit/transpolicy/tpsd/pdf/future_churchill.pdf

- Federal, Territorial and Provincial Sub-Working Group on Northern Transportation. (2015, March). *Report on winter roads*. Ottawa, ON: Transport Canada.
- Government of Alberta. (2013). *Alberta protects roads, bridges against future flood damage*. Retrieved from <http://alberta.ca/release.cfm?xID=35441D7B4B5CB-CC92-86D4-DF91A48CA0C5B1FC>
- Government of Manitoba. (2011). *Red river floodway*. Retrieved from <http://www.gov.mb.ca/flooding/fighting/floodway.html>
- Government of Manitoba. (2015a). *Transportation: Seaport at Churchill, Manitoba*. Retrieved from <http://www.gov.mb.ca/jec/invest/busfacts/transport/port.html>
- Government of Manitoba. (2015b). *Infrastructure and transportation: 2015 Manitoba spring road restrictions (SRR) Program*. Retrieved from <http://www.gov.mb.ca/mit/srr/>
- Government of Manitoba. (2015c). *Infrastructure and transportation: Water management and structures*. Retrieved from <http://www.gov.mb.ca/mit/wcs/index.html>
- Government of Manitoba. (2015d). *Manitoba 511 – Road and traveler information*. Retrieved from <http://www.gov.mb.ca/mit/roadinfo/>
- Government of Saskatchewan. (n.d). *Road conditions – Highway hotline*. Retrieved from <http://www.saskatchewan.ca/live/transportation/highway-hotline>
- Hochheim, K., and Barber, D. (2014). An update on the ice climatology of the Hudson Bay system. *Arctic, Antarctic, and Alpine Research*, 46(1), 66-83.
- ICF Marbek. (2012). *Climate change risk assessment and adaptation report: Ministry of Transportation*. Submitted to Alberta Department of Environment and Sustainable Resource Development, Climate Change Secretariat. Retrieved from http://www.transportation.alberta.ca/Content/docType29/Production/Climate_Change_Risk_Assessment.pdf
- Intergovernmental Panel on Climate Change (IPCC). (2013). *Climate change 2013: The physical science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Retrieved from https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SummaryVolume_FINAL.pdf
- International Civil Aviation Organization Secretariat. (2010). *ICAO Environmental report: Aviation and adaptation to climate change*. Retrieved from http://www.icao.int/environmental-protection/Documents/EnvironmentReport-2010/ICAO_EnvReport10-Ch6_en.pdf
- James, T., Henton, J., Leonard, L., Darlington, A., Forbes, D., and Craymer, M. (2014). *Relative sea-level projections in Canada and the adjacent mainland United States*. Ottawa, ON: Geological Survey of Canada. Natural Resources Canada. Open file 7737. Retrieved from <http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulleweb&search1=R=295574>
- Kelm, R., and Wylie, N. (2008). *Which way is it moving? Guidelines for diagnosing heave, subsidence and settlement*. Houston, TX: Forensic Engineers Inc. Retrieved from http://www.foundationperformance.org/pastpresentations/Kelm_Pres_Doc-9Apr08.pdf
- Kharin, V., and Zwiers, F. (2000). Changes in extremes in an ensemble of transient climate simulations with a coupled atmosphere-ocean GCM. *Journal of Climate* (13) 21, 3760–3788.
- Kovacs, P., and Thistlethwaite, J. (2014). Industry. In F.J. Warren and D.S. Lemmen (Eds.), *Canada in a changing climate: Sector perspectives on impacts and adaptation* (pp. 135-158). Ottawa, ON: Government of Canada.
- Lackenbauer, W., and Lajeunesse, A. (2014). *On uncertain ice: The future of Arctic shipping and the Northwest Passage*. Calgary, AB: Canadian Defence and Foreign Affairs Institute. Retrieved from <http://www.policyschool.ucalgary.ca/sites/default/files/research/uncertain-ice-lackenbauer-lajeunesse.pdf>
- Lautala, P., Ahlborn, T., and Harris, D. (2008). *Synthesis of railroad engineering best practices in areas of deep seasonal frost and permafrost*. Michigan Tech Technology Transfer Outreach Publication, prepared for the University of Alaska, Fairbanks, AL.
- Lemmen, D.S, Vance, R.E., Campbell, I.A., David, P.P., Pennock, D.J., Sauchyn, D.J., and Wolfe, S.A. (1998). *Geomorphic systems of the Palliser Triangle, southern Canadian Prairies: Description and response to changing climate*. Ottawa, ON: Geological Survey of Canada Bulletin 521. 72 p.
- Lohse-Busch, H., Duoba, M., Rask, E., Stutenburg, K., Gowri, V., Slezak, L., and Anderson, D. (2013). *Ambient temperature (20°F, 72°F and 95°F) impact on fuel and energy consumption for several conventional vehicles, hybrid and plug-in hybrid electric vehicles and battery electric vehicle*. SAE Technical Paper 2013-01-1462.
- Manitoba East Side Road Authority. (n.d.). *The East Side transportation initiative*. Retrieved from <http://www.eastsideroadauthority.mb.ca/questions-and-answers.html>
- Manitoba Infrastructure and Transportation. (2011). *Winter roads in Manitoba*. Retrieved from <http://www.gov.mb.ca/mit/winter/index.html>
- Mekis, E., and Vincent, L. (2011). An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. *Atmosphere-Ocean*, 2, 163-177.
- Middleton, W. (2000). *Yet there isn't a train I wouldn't take: Railway journeys*. Bloomington, IN: Indiana University Press.
- Miller, P. (2014). *Winter's impact on railroad operations – Fact and fantasy*. Presentation at RAC Rail Day, Ottawa, ON, Dec. 2, 2014.
- Natural Resources Canada. (2016). *Learn the facts: Cold weather effects on fuel efficiency*. Retrieved from <http://www.nrcan.gc.ca/energy/efficiency/transportation/cars-light-trucks/buying/16748>

- Nurmikolu, A., and Silvast, M. (2013). Cause, effects, and control of seasonal frost action in railways. *Sciences in Cold and Arid Regions*, 5(4), 363-367.
- Port of Churchill. (n.d). About. Retrieved from <http://www.portofchurchill.ca/about>
- Rabson, M. (2012, January 6). *Winter road delays threaten water supply*. Retrieved from <http://www.winnipegfreepress.com/local/winter-road-delays-threaten-water-supply-fix-136796688.html>
- Railway Association of Canada. (2015). *Canada's railways: 2014 rail trends*. Retrieved from <http://www.railcan.ca/publications/trends>
- Sauchyn, D. (2010). Prairie climate trends and variability. In D. Sauchyn, H. Diaz and S. Kulshreshtha (Eds.), *The new normal: the changing Prairies in a changing climate* (pp. 32-40). Regina, SK: Canadian Plains Research Centre.
- Sauchyn, D., and S. Kulshreshtha. (2008). Prairies. In D.S. Lemmen, F.J. Warren, J. Lacroix, and E. Bush (Eds.), *From impacts to adaptation: Canada in a changing climate 2007* (pp. 275-328). Ottawa, ON: Government of Canada.
- Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., and Zhang, X. (2012). Changes in climate extremes and their impacts on the natural physical environment. In C. Field, V. Barros, T. Stocker, D. Qin, D. Dokken, K. Ebi, M. Mastrandrea, K. Mach, G. Plattner, S. Allen, M. Tignor, and P. Midgley (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation* (pp. 109-230). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK, and New York, NY: Cambridge University Press.
- Statistics Canada. (2005). *Land and freshwater area, by province and territory*. Retrieved from <http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/phys01-eng.htm>
- Statistics Canada. (2011). *Population and dwelling count highlight tables, 2011 census*. Retrieved from <http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/hltfst/pd-pl/Table-tableau.cfm?LANG=Eng&T=101&S=50&O=A>
- Statistics Canada. (2013). *Shipping in Canada 2011*. Retrieved from <http://www.statcan.gc.ca/pub/54-205-x/2011000/part-partiel-eng.htm>
- Statistics Canada. (2014a). *Gross domestic product, expenditure-based, provincial and territorial*. Retrieved from <http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=3840038>
- Statistics Canada. (2014b). *CANSIM Table 401-0045: Air cargo traffic and flights*. CANSIM Database. Retrieved from <http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=4010045>
- Szeto, K., Brimelow, J., Gysbers P., and Stewart, R. (2015). The 2014 extreme flood over the southeastern Canadian Prairies. *Bulletin of the American Meteorological Society*, 96(12), 20-25.
- Taylor, S., and Parry, J. (2014). *Enhancing the resilience of Manitoba's winter roads system*. International Institute for Sustainable Development. Retrieved from https://www.iisd.org/sites/default/files/publications/winter_roads.pdf
- Tivy, A., Alt, B., Howell, S., Wilson, K., and Yackel, J. (2007). Long-range prediction of the shipping season in Hudson Bay: A statistical approach. *Weather and Forecasting*, 22, 1063-1075.
- Transport Canada. (2014). *Transportation in Canada 2013: Overview report and addendum*. Retrieved from <https://www.tc.gc.ca/eng/policy/anre-menu-3045.htm>
- Transport Canada. (2015). *Transportation in Canada 2014: Overview report and addendum*. Retrieved from <https://www.tc.gc.ca/eng/policy/anre-menu-3045.htm>
- Transportation and the Environment Task Force. (2014). *Transportation and the environment: Task force report*. Ottawa, ON: The Council of Ministers Responsible for Transportation and Highway Safety. Retrieved from <http://www.comt.ca/reports/transportandenviron-1014.pdf> and Appendix A <http://www.comt.ca/reports/transportandenviron-app-1014.pdf>
- Transportation Research Board. (2008). *Climate change impacts on US transportation infrastructure. Transportation Research Board Special Report 290*. Washington, DC: National Research Council of the National Academies.
- Transportation Safety Board of Canada. (2013). *Rail investigation reports*. Retrieved from <http://www.bst-tsb.gc.ca/eng/rapports-reports/rail/>
- Tweed, M. (2015). *OmniTRAX Canada*. [Presentation]. *Warming of the North 2015*. Ottawa, ON. Retrieved from <http://umanitoba.ca/faculties/management/ti/warming-of-the-north-2015-speakers.html>
- Vincent, L., Wang, X., Milewska, E., Wan, H., Yang, F., and Swail, V. (2012). A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. *Journal of Geophysical Research*, 117, D18110, doi:10.1029/2012JD017859.
- Wang, T., Samsom, S., Ng, A.K.Y., and Earl, P. (2016). Climate change and the adaptation planning of inland port and rail infrastructures in the province of Manitoba in Canada. In A.K.Y. Ng, A. Becker, S. Cahoon, S.L. Chen, P. Earl, and Z. Yang. (Eds.), *Climate change and adaptation planning for ports* (pp. 59-73). Abingdon, UK: Routledge.