# 3 · Northern Territories

# CHAPTER 3:
# NORTHERN TERRITORIES

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## KEY FINDINGS

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

## 1.0 INTRODUCTION

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

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

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

## 1.1 REGIONAL OVERVIEW

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

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

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

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

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

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

## 2.0 AN INTRODUCTION TO CANADA'S NORTHERN TRANSPORTATION SYSTEM

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

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

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

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

### 2.1 SYSTEM OVERVIEW

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

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

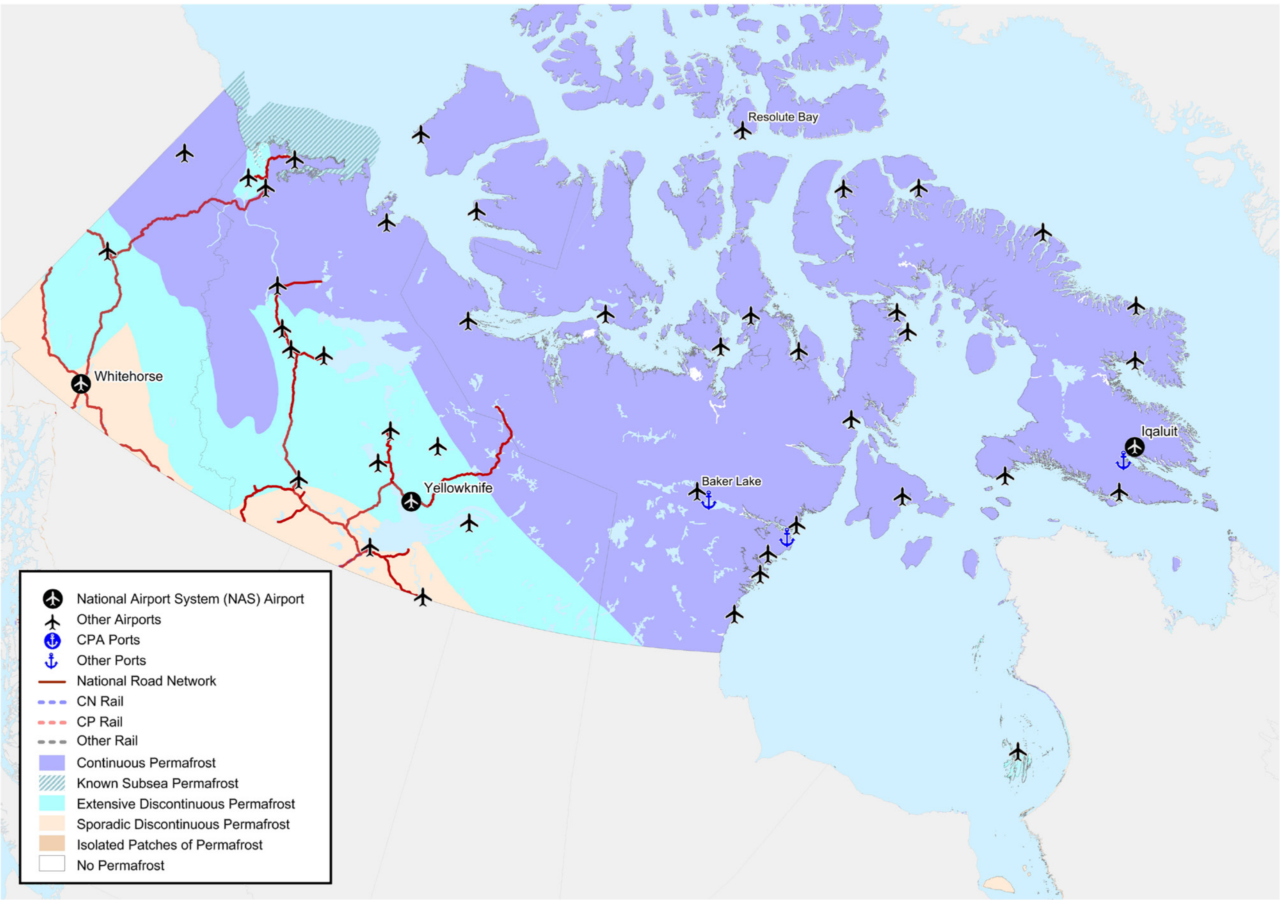

**Table 2: Transportation networks in the territories at a glance.**

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

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

## 2.2 ROAD TRANSPORTATION

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

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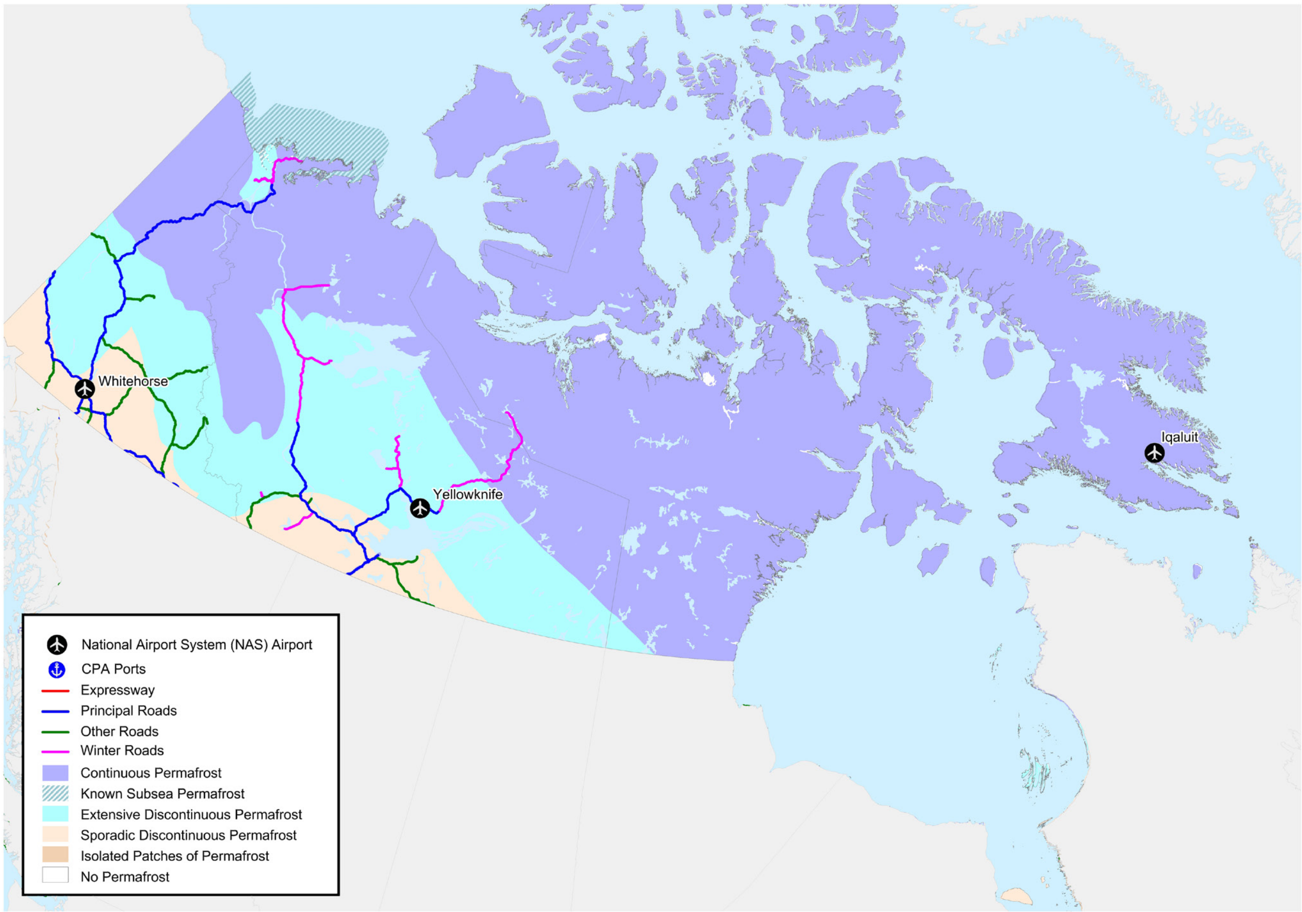
[2] Aerodrome: Any area of land, water (including the frozen surface thereof) or other supporting surface used or designed, prepared, equipped or set apart for use either in whole or in part for the arrival, departure, movement or servicing of aircraft and includes any buildings, installations and equipment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

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

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



## 2.3 AVIATION

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

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

## 2.4 MARINE TRANSPORTATION

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

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

## 2.5 RAIL TRANSPORTATION

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

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

# 3.0 CLIMATE

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

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

## 3.1 TRENDS AND PROJECTIONS

### 3.1.1 ATMOSPHERE

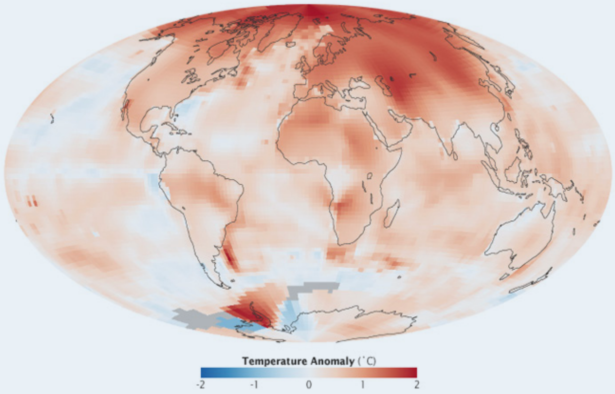
Arctic regions have warmed, and will continue to warm, more rapidly than most regions of the world, due in part to the phenomenon known as Arctic amplification (see textbox). Canada's North has already experienced some of the most significant surface air temperature warming observed anywhere on the planet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

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

### WHAT IS ARCTIC AMPLIFICATION?

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

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



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

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

### 3.1.2 CRYOSPHERE

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

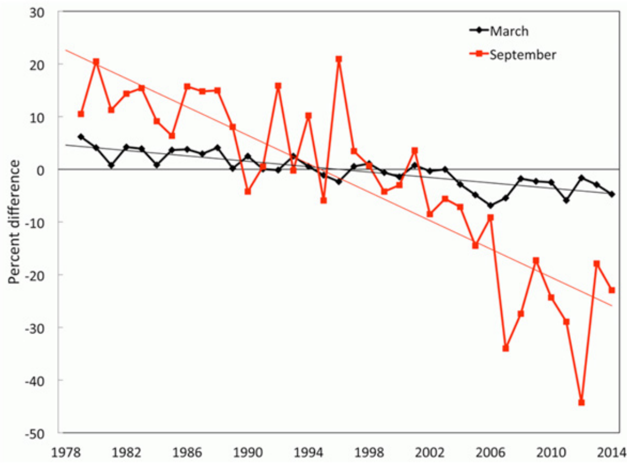
Sea ice is one of the most defining features of Canada's North (Ford et al., 2016). In winter, when ice cover is essentially complete, the coast is protected from wave action, and ice permits transportation between communities and access to hunting and fishing areas. When ice is in motion, wind and currents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

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

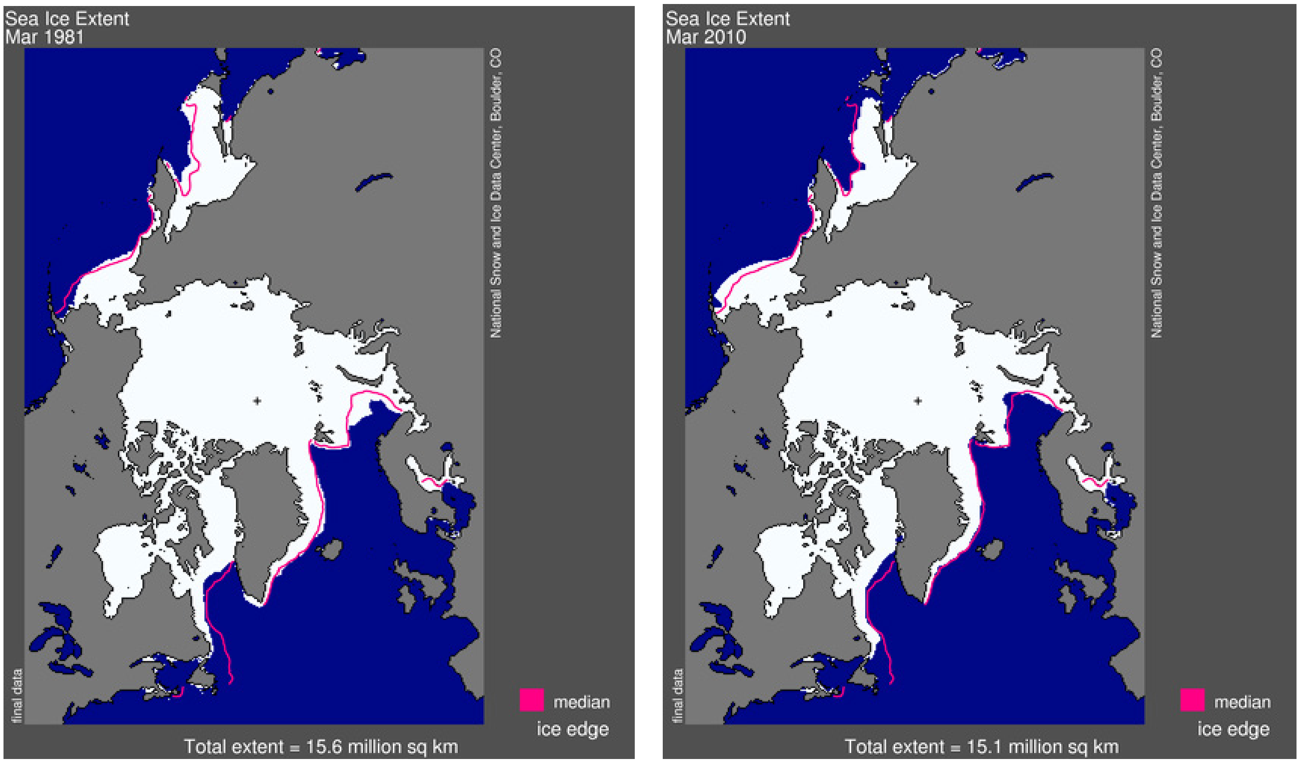
These trends in sea-ice cover are expected to continue or accelerate (Vaughn et al., 2013), with some models projecting almost complete loss of summer ice cover before mid-century (Wang and Overland, 2012). Arctic sea ice is also thinning, with the average spring ice thickness projected to decrease from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

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

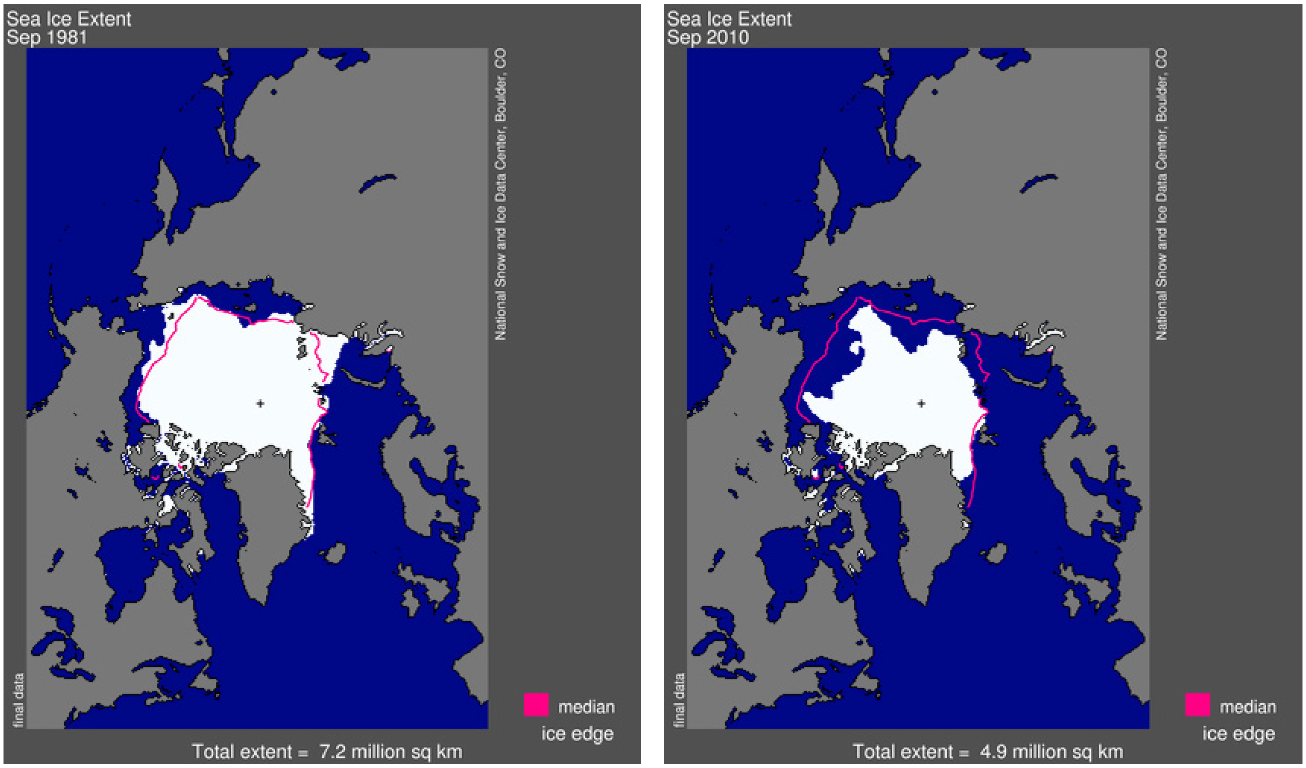
**4a –** Annual sea-ice extent anomalies (relative to the mean values for the period 1981–2010) for the months of maximum and minimum ice extent (March and September, respectively). (Perovich et al., 2014)



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



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



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

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

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

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

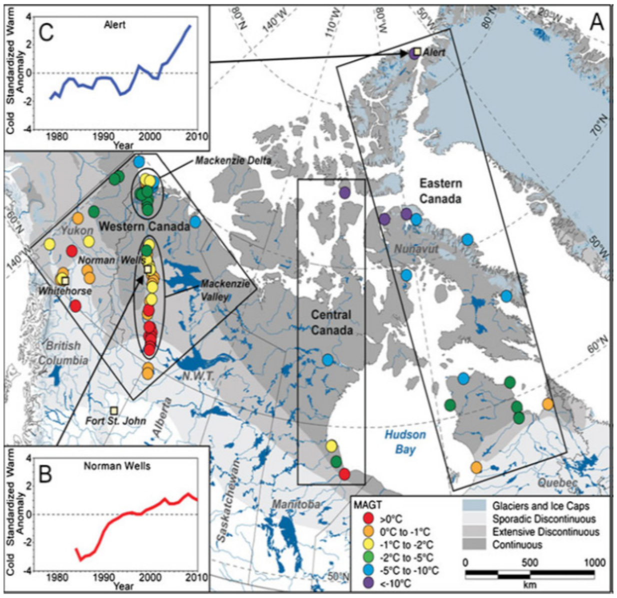
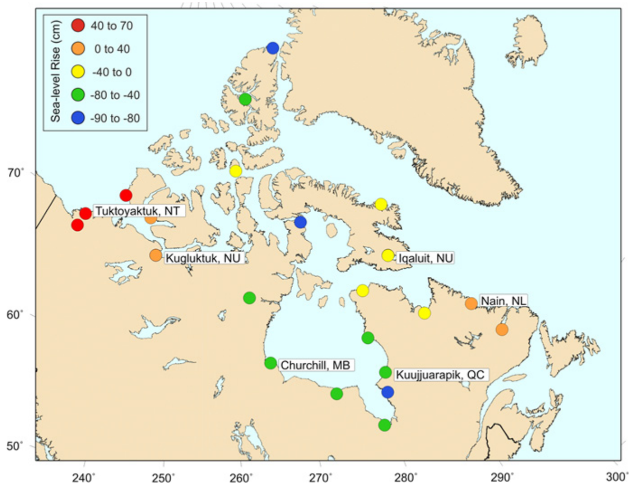


**Figure 6: Projected median relative sea-level change in 2100 for a high greenhouse gas emissions scenario (RCP8.5; after James et al., 2014).** The scenarios and methods used are described in Atkinson et al., 2016. (Source: Natural Resources Canada)



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

### 3.1.3 SEA LEVEL

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

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

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

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

# 4.0 ROAD IMPACTS AND ADAPTATION

## 4.1 CLIMATE IMPACTS ON ROAD TRANSPORTATION

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

### 4.1.1 ALL-SEASON ROADS

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

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

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

### 4.1.2 WINTER ROADS

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

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

## 4.2 FUTURE RISKS

### 4.2.1 ALL-WEATHER ROADS

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

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

### 4.2.2 WINTER ROADS

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

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

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

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

***TCWR Facts:***

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

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

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

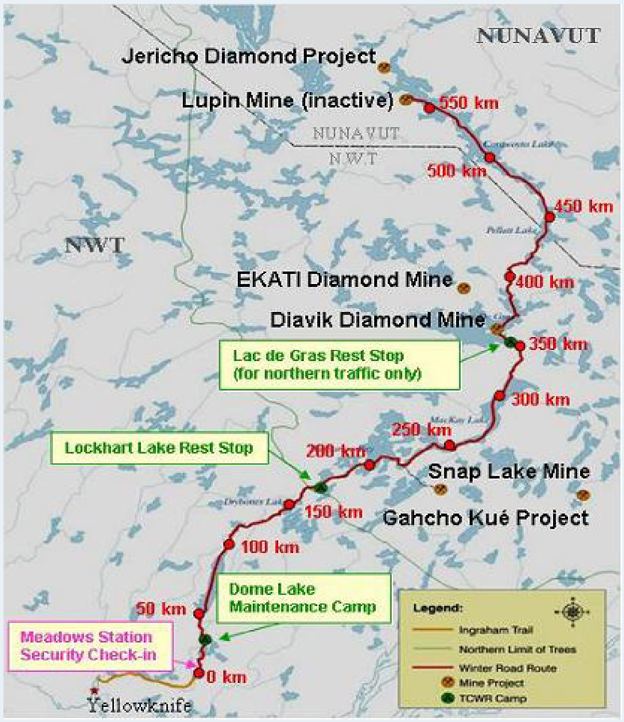
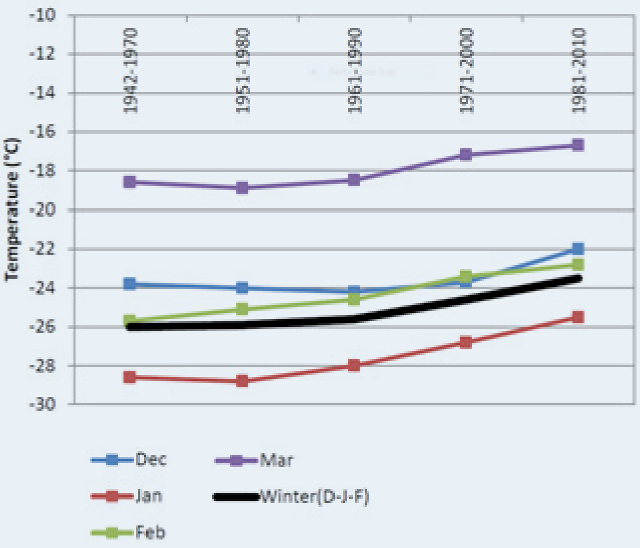


**Figure 9: Historical average temperatures observed in Yellowknife for five previous climate normal periods.** (Source: Environment and Climate Change Canada)



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

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

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

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

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

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

## 4.3 ADAPTATION PRACTICES

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

### 4.3.1 MAINTENANCE AND MONITORING PRACTICES

#### 4.3.1.1 All-weather roads

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

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

#### 4.3.1.2 Winter roads

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

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

### 4.3.2 INFRASTRUCTURE PLANNING/SITING

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

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

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

### 4.3.3 CONSTRUCTION TECHNIQUES AND TECHNOLOGIES FOR ALL-WEATHER ROADS

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

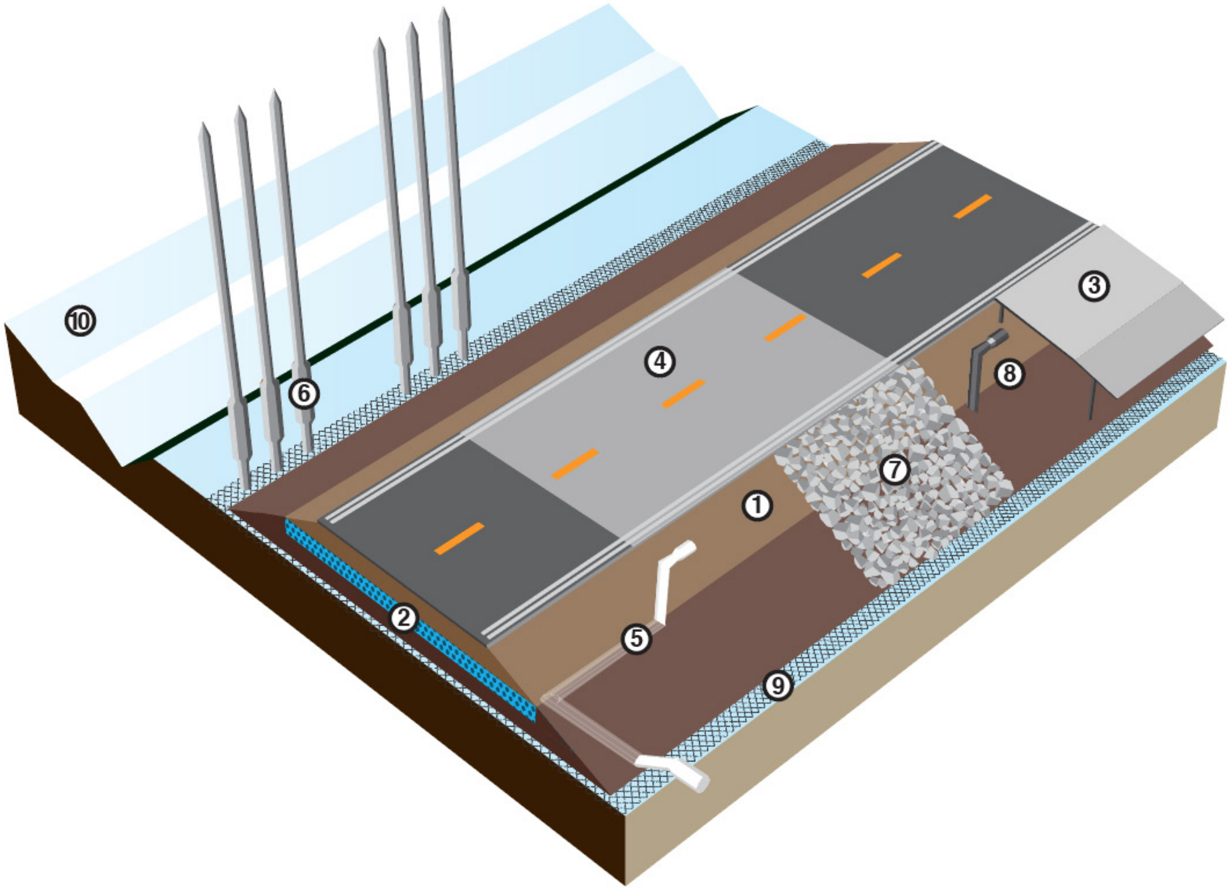
**Table 3: Comparing the applicability and relative cost of adaptation techniques for northern roads.** (Source: Beaulac and Doré, 2006)

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

🟩 Suggested application. 🟦 Application possible but not optimal

N/A: not applicable; N/R: not recommended
*NOTE - $, $$, $$$, $$$$, $$$$$ is a relative scale, where $ presents the lowest relative cost and $$$$$ the highest.*
**Reflective or high-albedo surfaces do not necessarily have high levels of maintenance. Levels vary depending on application.*

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



Methods to limit heat intake under roads include:

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

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

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

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

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

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

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

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

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

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

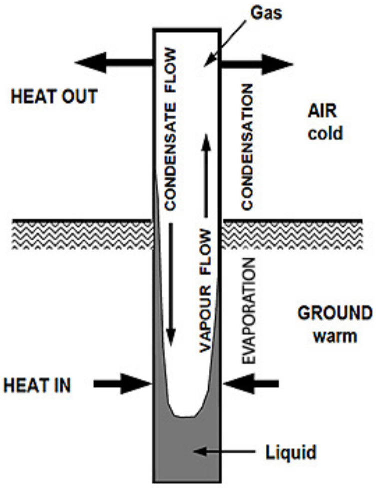


**Figure 13: Flat-loop thermosyphon foundation at an airport maintenance garage in Inuvik, NT.** (Source: Igor Holubec)

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

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

Methods to enhance the stability of embankments include:

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

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

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

CASE STUDY 2

## CASE STUDY 2: TESTING TECHNIQUES TO PREVENT PERMAFROST THAW

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

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

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

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

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

*Written by Katerine Grandmont (Cold Regions Geomorphology and Geotechnical Laboratory, Université de Montréal).*

## 5.0 RAIL TRANSPORTATION

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

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

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

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

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

# 6.0 AIR TRANSPORTATION

## 6.1 CLIMATE IMPACTS ON AIR TRANSPORTATION

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

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

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

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

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

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

## 6.2 FUTURE RISKS

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

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

## 6.3 ADAPTATION PRACTICES

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

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

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

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

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

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

## CASE STUDY 3: INFRASTRUCTURE IMPROVEMENTS AT IQALUIT INTERNATIONAL AIRPORT

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

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

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

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## 7.0 MARINE TRANSPORTATION

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

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

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

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

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

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

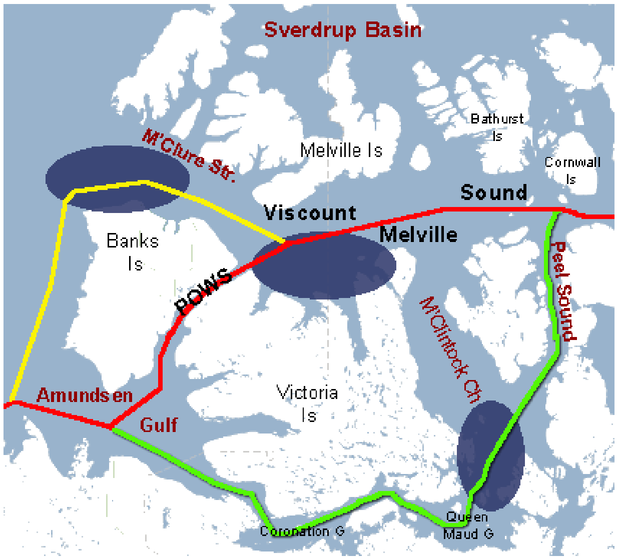
For river transportation, lower water levels have required the use of lighter barges or smaller loads to maintain safety standards, in some cases disrupting operations (Deton'Cho-Stantec, 2013). For example, low water levels in the Mackenzie River have delayed the shipment of goods to northern communities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

## 7.2 FUTURE RISKS AND OPPORTUNITIES

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

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

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



CASE STUDY 4

## CASE STUDY 4: HAS THE NORTHWEST PASSAGE BECOME VIABLE?

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

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

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CASE STUDY 5

## CASE STUDY 5: RESOURCE DEVELOPMENT IN THE BEAUFORT SEA REGION

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

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

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

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

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

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

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

## 7.3 ADAPTATION PRACTICES

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

### 7.3.1 ADAPTATIONS FOR VESSELS AND NAVIGATION

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

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

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

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

### 7.3.2 ADAPTATIONS FOR MARINE FACILITIES

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

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

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

## 8.0 INFORMATION GAPS

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

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

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

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

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

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

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[5] See: Blais-Stevens and Behnia (2015)

## 9.0 CONCLUSIONS

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

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

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

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