Economic Implications of Climate Change

Adaptations for Mine Access Roads in Northern Canada

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YUKON RESEARCH CENTRE • Yukon College

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EXECUTIVE SUMMARY

Climate change is one of the major threats to northern infrastructure in Canada. The mining industry is particularly vulnerable to climate change, and in the Canadian North the effects of climate change on mining-related transportation have become a significant concern. Climate-driven disruptions to mine access roads have caused economic losses and raised concerns about projected future changes in the region.

This study evaluates the climate-related vulnerabilities and related costs and benefits of the Tibbitt to Contwoyto Winter Road (TCWR), a mine access road built mainly over frozen lakes in the northeastern region of the Northwest Territories (NWT). The TCWR is the main access road for three active diamond mines, as well as one that will be active in the next year, and is the busiest heavy-haul ice road in the world. Diamond mining in this region has been a major contributor to the NWT economy. The road is operated by a joint venture between three mining companies, with contracted support for engineering, maintenance and security. Companies transport goods via the winter road to supply year-round operations. When the road season is cut short, supplies must be transported by plane or helicopter, which greatly increases costs. One of the main goods being transported to the mines is diesel to power mine operations.

The vulnerability study identified five climate variables that affect the viability of the TCWR to supply the mines:

- operational season length (interaction of freezing-degree days and melting-degree days);
- incidence of temperature swings in excess of 18˚C;
- incidence of consecutive days above 0˚C during the operational season;
- amount of snow on the ground January 1; and
- number of extreme cold events during the operational season.

Under historical climate conditions, the TCWR is generally resilient; however, from the analysis of these five climate variables, the length of the operational season — driven by temperature — was identified as the key vulnerability. Two future scenarios were identified for the road based on the vulnerability of the road's operational season length to temperature (freezing-degree-days and melting-degree-days) and an analysis of potential adaptations.

The two scenarios capture the impact on the road of increasingly difficult climate conditions. The first is an adaptation scenario based on difficult climate conditions, leading to shorter operational seasons as maintenance and repairs become more difficult and costly. The second is a critical conditions scenario based on highly challenging climate conditions, leading to late opening, early closure, or non-opening of the road where the desired levels of road access become impossible and other modes of transportation are required to move loads.

The economic analysis evaluated the impact of multiple climate variables and their thresholds on the two scenarios. The affected cost types, affected stakeholders and thresholds were identified for each variable.

The key cost types that increased net costs for the adaptive scenario include flexible scheduling, and increased construction and maintenance for the ice road, portages and ramps. The greatest cost increase is from adaptive scheduling on the part of carriers. If the season is shortened below 50 days, additional costs are triggered as loads are shifted. Over the assumed 35-year time horizon the total estimated costs of the adaptive scenario are in the order of $55 million. This was the mean value produced by the economic analysis, with a maximum cost value of $155 million and a 60% probability that the actual value of the costs would be greater than $55 million.

An operational season length of less than 45 days was identified as the trigger for the critical conditions scenario. At that point the road would no longer be able to accommodate an average season's demand. The two key cost types that increased net costs for the critical conditions scenario are using alternative forms of transportation and production loss. The expected total cost over the 35-year time horizon is $213 million, of which production loss is the dominant cost, at approximately 70% of the total. The maximum value for this scenario is $1.8 billion, with a 60% probability that the actual value of the costs would be greater than $213 million. The results of the analysis are highly sensitive to the assumed forecast in operational season length, which implies that small changes in season length would result in large and significant future damages under this scenario.

Operational season length is the most important cost driver in the future, partly because some of the other climate-cost variable interactions are likely to become less of a concern with climate change, or remain unaffected by it. Some of the less important climate-cost interactions, such as construction costs, have much smaller incremental effects even when triggered by the adaptive scenario. The operational season, on the other hand, has a significant impact on carrier costs in the adaptive scenario and on both the need for alternative transportation and production costs in the critical conditions scenario. The results indicate that if the demand continues at current levels, the expected evolution of operational season length creates a significant economic risk to TCWR operators and users.

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1.0 INTRODUCTION

Climate change has widespread implications for both private and public infrastructure in Canada's North. The mining sector is a fundamental component of the Canadian economy, contributing more than $10 billion per year and employing almost 50,000 people in primary mineral extraction alone (Pearce et al. 2009). The northern mining sector makes up 20% of Canada's mineral production (Pearce et al. 2009).

The mining industry's dependence on the natural environment makes it particularly vulnerable to climate change. In the Canadian North, the effects of climate change — particularly on mining-related transportation — have become a significant concern (Perrin et al. 2015). Over the past decade, some mines have experienced unusually significant economic losses as a result of climate-driven disruptions to mine access roads, including shortened winter road seasons and large road washouts due to flooding (Ashbury 2006). Projected increases in extreme weather events and changes in average climate conditions will likely disrupt ground-based transportation routes and operations even further, through increasingly significant effects on permafrost, lake and river ice, higher numbers and intensities of land and snow slides, severe runoff and flooding events, and erosion, among other factors.

Northern jurisdictions have identified the need for greater understanding of the implications of climate change on infrastructure, and of how to quantify the costs of adapting to this change. Key policy documents such as *Canada's Northern Strategy* (INAC 2009) and the *Pan-Territorial Adaptation Strategy* (GNWT, GN and YG 2011) emphasize the importance of critical northern industries working to further assess and manage the risks of climate change.

Generally speaking, ground-based access has been extremely important to the production, safety and economic growth of the northern mining sector (Nelson and Schuchard 2011; Pearce et al. 2009). As a result, northern governments, professional associations and the mining sector have all expressed interest in enhancing their understanding of options for adapting to the impacts of climate change. Proactive adaptation to climate change can lower the overall cost of climate impacts by moderating or preventing damage, shortening service disruptions, and reducing risks to human health and safety (NRTEE 2011). Relatively little work has been done in northern Canada to assess the costs and benefits of adaptation with respect to mine access roads.

This project brings together the expertise of the Northern Climate ExChange, the International Institute for Sustainable Development, Risk Sciences International, Nodelcorp Consulting and EnviroEconomics to develop a cost-benefit analysis of a range of adaptation options for a major northern mine access road. The project focuses on a case study analysis of the Tibbitt to

Contwoyto Winter Road (TCWR). The road was chosen due to its sensitivity to climate and its regional economic importance, and because of the availability of existing research and analysis. Mining is a key part of the economy of the Northwest Territories, and the viability of the TCWR in the future is a key concern for the existing and potential mines along its route.

This report provides background information on the road, including projected climate conditions for key parameters related to road operations, a step-by-step description of the methodology used to estimate the economic implications, a summary of the results of that analysis, and some key findings from the project.

The results of this study provide valuable information for road owners and stakeholders using the Tibbitt to Contwoyto Winter Road, and for decision-makers planning for changes to the road. The results provide a better understanding of climate thresholds for future years and how crossing those thresholds will affect costs. The economic information provided in Sections 3.4 to 3.6 will help road owners anticipate the magnitude of costs that they may incur during shorter seasons. With shorter seasons potentially happening more frequently, the findings provide additional information for decision-makers to consider as they assess whether to build an all-season road.

The findings can also inform future planning, economic assessments and vulnerability studies for other northern roads, particularly winter roads. The methodology can be applied to other supply roads in northern jurisdictions, and the information on key climate vulnerabilities can inform other winter road managers.

2.0 CASE STUDY

The Tibbitt to Contwoyto Winter Road (TCWR), formerly known as Echo Bay Mines Limited's Lupin Winter Road, was originally constructed to supply the Lupin Gold Mine at Contwoyto Lake in what is now Nunavut. The road currently supplies four mines and is the only overland supply route. It provides access for reclamation efforts at former mines, including the Tundra Mine (which was reached by a spur road during the 2015 season).[1] It also supplies some exploration properties, contaminated site remediation projects, and tourism and outfitting camps, although third-party traffic of this type is minimal (Greenspan 2008).

The road is operated by the Tibbitt to Contwoyto Winter Road Joint Venture Management Committee (JVMC), which is made up of the Dominion Diamond Ekati Corporation (Ekati mine), Diavik Diamond Mines Inc. (Diavik mine) and DeBeers Canada Inc. (Snap Lake and Gahcho Kué

[1] A winter road year is the year in which the operating season occurs (i.e., January – April)

mines). The JVMC is also responsible for contracting companies for construction, engineering and security services for the winter road.

The TCWR is the busiest heavy-haul ice road in the world (Tetra Tech EBA 2013), with a record 10,922 loads and 330,002 tonnes (t) hauled in 2007 (JVMC 2013). Since 2001 the road has seen increased traffic, which has also brought greater regulatory scrutiny (Tetra Tech EBA 2013). The road is used to bring in diesel fuel, cement, tires and explosives supplies, in addition to other manufacturing and construction materials and equipment.

The TCWR has been celebrated for advancing engineering practices for ice roads and for contributing to the development of the northern mining industry. Notably, the JVMC won a Professional Award of Merit from the Northwest Territories and Nunavut Association of Professional Engineers and Geoscientists for "its combined engineering, human and socio-economic achievements" (Tetra Tech EBA 2014).

2.1 ROAD DESCRIPTION

The road starts at Tibbitt Lake at the end of Highway 4, approximately 70 kilometres (km) northeast of Yellowknife (Figure 1). Originally, the road was 600 km in length, ending at Lupin Gold Mine at Contwoyto Lake, Nunavut, until it was extended to reach Shear Minerals' Tahera Diamond Corporation Mine (JVMC 2013). Neither of these mines is currently in operation and the road now ends around the Diavik and Ekati Diamond Mines, at around the 400-km mark.

The TCWR travels generally north and northeast, and links to the Snap Lake Diamond Mine, Diavik Diamond Mine and Ekati Diamond Mine, as well as the Gahcho Kué Project (Nuna Logistics 2014). Camps, shops, laydown areas for equipment storage, and fuel stores are strategically positioned along the road, which allows construction and maintenance teams to respond quickly to issues as they arise.

The TCWR provides dedicated service to the operating mines along the route. The road must deliver specified tonnages of goods to the mines over the operational season. If severe weather events interrupt the operation of the road, or shorten its operating season, lost service can be recovered in most cases by increasing the number of daily loads during the season. During the operating season, road operations can be run later into the evening, or even 24 hours a day, until the loss is recovered, the limiting factor being the number of trucks and drivers available. This flexibility has a significant impact in reducing the severity of events. Even though road operations are interrupted, the overall load levels through the operating season can be maintained.

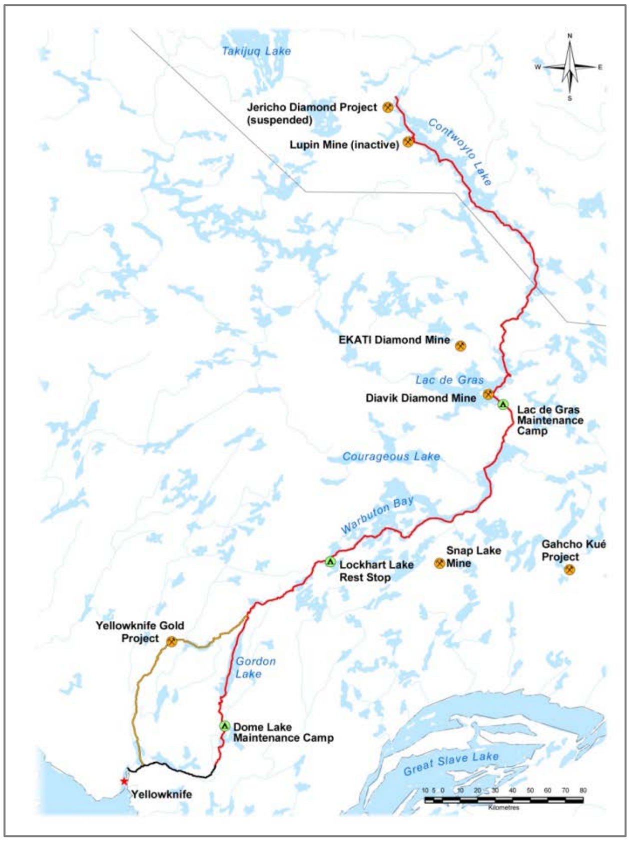

Figure 1: Map of Tibbitt to Contwoyto Winter Road

Source: JVMC 2012

This is an unusual feature of this particular winter road. It may not be shared by other winter roads in northern Canada, where there is more interest in using the road consistently over the season as opposed to delivering a certain number of loads. For example, winter roads that provide access to northern communities may not see the same amount of high-volume loads, but will be used for as long as possible in the season.

2.2 GEOGRAPHICAL ELEMENTS

The TCWR travels north and northeast from Yellowknife through two ecozones: the Taiga Shield and the Southern Arctic. It crosses lakes, streams, boreal forest, a transitional zone and barrenlands terrain; most of the road passes over frozen lake surfaces. The overland traverses, called portages, generally follow low-lying terrain, including frozen streams and wetland areas near lakes. In hilly areas the road follows existing grades as much as possible. From Yellowknife to the Mackay Lake region the road passes through the Taiga Shield Ecozone. This area is below the tree line and the portages or overland stretches pass through the boreal forest. On some portages, trees and taller shrubs have been cleared; other portages have been affected by forest fires. North of Mackay Lake the road passes through the Southern Arctic Ecozone, which is barrenland characterized by shrub tundra. The transition area between the two ecozones, the Coppermine River Upland ecoregion, is made up of open stands of stunted trees (EBA 2001).

2.3 ROAD DESIGN AND CONSTRUCTION

Design and construction of the TCWR is a collaborative effort that is undertaken every year by the JVMC, engineering consultants and the construction firm. The road is designed based on the upcoming season's supply needs and schedules and on terrain, safety and environmental concerns. The maximum loads are based on a minimum ice thickness of 107 centimetres (cm). Planning for the next season needs to start early and involves projections of supply needs and schedules for the upcoming year (Jarvis and Proskin 2011).

Nuna Logistics has been constructing and maintaining the TCWR since 1998. Along with construction and maintenance, the company is responsible for truck dispatching, traffic control, camp catering and summer camp maintenance.

The road was first built in 1982. Construction of the road generally begins in December or January and takes approximately five to six weeks to complete. Historically, the road is open for eight to ten weeks, starting anywhere from January 26 to February 11 and ending anywhere from March 21 to April 16. In recent years it has opened before February 4 and closed by April 1. The average number of operational days per year is 67 (JVMC 2013).

The operating season for roads built over ice and compacted snow is sensitive to temperature and other winter weather and climate conditions such as early- and late-season snowfalls (Mesher, Proskin and Madsen 2008). Ice thickness and quality and overland portages are particularly sensitive to rapid thawing (Comfort and Abdelnour 2013; Hayley and Proskin 2008; McGregor, Hassan and Hayley 2008; Rawlings, Bianchi and Douglas 2009). The ongoing trend of winter warming and shortened road seasons, as demonstrated in Appendix A, places resupply at risk and also creates a perverse incentive to weigh operator safety against time and volume constraints (McGregor, Hassan and Hayley 2008).

The majority of the road (approximately 87%) is built over lake ice and must be reconstructed each year (JVMC 2013). The ice thickness is measured daily and profiled by ground-penetrating radar. Ice sheet profiling is carried out throughout the season and the results are compared with the data collected through quality assurance/quality control checks performed by an engineering firm (JVMC 2013).

Construction of the road requires special lightweight equipment, including amphibious track vehicles equipped with ground -penetrating radar. Helicopter surveillance identifies ice cracks or other hazards and supports construction with information as the machines move forward. Snow cover insulates the ground or ice beneath it, so various types of low-ground-pressure equipment — which are better able to float on soft ground surfaces — are used to keep the road clear. This helps keep portages smooth and promotes the continual build-up of ice (Nuna Logistics 2014).

The road is 50 metres (m) wide on lakes and 12 to 15 m wide on portages. Sections that cross lakes are plowed wider than portages to ensure that the ice thickens in the driving lanes. Due to the insulating effect of snow, ice underneath the snow banks can be thinner, weaker and may be cracked (JVMC 2012). There are 65 overland portages between lakes, which are upgraded as necessary with gravel and sand pads. In some years, a secondary winter road route has been constructed by RTL Robinson Enterprises. It provides an alternate route for the southernmost 110 km.

Historical GPS coordinates are used to ensure that the TCWR crosses the deep areas of the lakes while avoiding rocky shoals. Shoals are potential weaknesses, because deflection of the ice onto shoals can erode the ice from below (JVMC 2013).

Road monitoring and maintenance are conducted throughout the season on both the primary and secondary routes. This includes monitoring ice integrity, repairing cracks, filling potholes, clearing snow, dealing with overflow and sanding portages.

2.4 ROAD TRAVEL

Trucks hauling fuel and supplies to the mines operate at a normal gross vehicle weight (GVW) of 63,500 kilograms (kg), with maximum loads of up to 100,000 kg (McGregor, Hassan and Hayley 2008). Load weight limits are based on the minimum ice thickness of the entire route. The minimum ice thickness for hauling is 70 cm; only very light loads can travel at that point. As the ice thickness increases, the allowable load weight rises commensurately. With an ice thickness of 107 cm, a load of 42 t can travel on the ice. This is the equivalent of a Super B tanker fully loaded with 50,000 litres (l) of fuel. In the past, the road allowed for a maximum of approximately 800 loads per year, but with improved engineering the road can now handle up to approximately 10,000 loads per year. Load numbers and ice thickness are recorded and communicated to the public through the TCWR website (JVMC 2013).

EBA Engineering Consultants, Ltd. (now Tetra Tech EBA, Inc.) is one of the firms that provide engineering support for the risk management program of the TCWR. These services include measuring ice strength, analyzing ice-carrying capacity for standard and heavy loads, and collecting data on ice thickness and bathymetry (Tetra Tech EBA 2013). The data collected by

Tetra Tech EBA is compared with that coming from Nuna Logistics to ensure that construction and operation measurements are accurate.

NOR-EX Ice Engineering has provided engineering support for the TCWR since 2013, including a project in 2014 that focused on ice engineering and quality assurance. The project reviewed ice engineering procedures, developed new loading charts and conducted ice tests. This resulted in fewer truckloads and increased payload capacity for the 2014 season (NOR-EX Ice Engineering 2014).

There are three maintenance camps along the road: Dome Lake, Lockhart Lake and Lac de Gras (see Figure 1). The camps allow for the storing of materials, equipment and fuel, and provide housing for maintenance and security staff. There is also a security check point at the Meadows Dispatch at the beginning of the road. Drivers are required to comply with JVMC rules and regulations, including speed limits, and a 24-hour patrol enforces those rules. Security is provided by Deton'Cho/Scarlet Security Services, who deploy 15 to 18 officers based out of the maintenance camps and provided with radar-based speed detection devices. Regular inspections are also conducted by the Royal Canadian Mounted Police, federal and territorial government representatives, and the JVMC (JVMC 2013).

The JVMC provides drivers with training and a written rule book, updated yearly, entitled *Winter Road Regulations and Rules of the Road*. It provides information on speed limits and other restrictions, and instructions for behaviour on the TCWR (JVMC 2012). The speed limit on lakes is 25 km/hour when fully loaded, 35 km/hour when empty, and 10 km/hour for all weights in a flood zone (damaged ice surfaces are repaired by being flooded). The speed limit on portages is 30 km/hour, with a 10-km/hour speed limit for traveling on and off portages. Empty trucks can drive 60 km/hour in “express lanes,” which are southbound return lanes built on larger lakes. The secondary route is also sometimes used for southbound traffic. Speed limits and spacing restrictions of 0.5 km between trucks are not only important for road safety, but are also key elements in maintaining the integrity of the winter road ice surface and prolonging the operating season (JVMC 2013).

3.0 ESTIMATING ECONOMIC IMPLICATIONS

The methodology used to evaluate the economic effects on the TCWR driven by climate change employs the framework detailed in *The Economic Implications of Climate Change on Transportation Assets: An analysis framework* (Sawyer 2014).This study combines the Sawyer methodology with a conceptual framework developed specifically for the TCWR and described in the steps below. Using this combination of established practice with a custom framework ensures that analysis will be both rigourous and rooted in best practice.

The following steps were undertaken to produce the analysis.

- **Step 1: Hazard, Vulnerability and Assets at Risk**. A literature review and Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol (Engineers Canada 2014) were used to identify key relationships between climate, road operations and adaptive responses.

- **Step 2: Climate Conditions and Forecast**. A PIEVC workshop was held in Yellowknife with TCWR stakeholders to identify high-priority climate variables that affect road operations. Forecasts for these weather variables were then developed using detailed analytics.

- **Step 3: Assessment Scenarios.** Assessment scenarios were identified for estimating economic outcomes of climate risks. Two scenarios were identified as being useful to understand the climate-related links between weather and winter road operations: 1) an *Adaptive Scenario* reflects operational changes that enable road operations to continue, albeit at higher costs; and 2) a *Critical Conditions Scenario* reflects an increased probability of more frequent road closures due to climate.

- **Step 4: Economic Assets at Risk and Forecasts**. The literature review, PIEVC process outcomes, and interviews with road operators, users and government formed the basis of the identification of key costs and their drivers.

- **Step 5: Climate Risk and Economic Value Assessment**. This step combined the climate risks and the economic costs into relationships driven by weather variables. The economic costs under the two scenarios were estimated using Monte Carlo analysis, which uses probability distributions for all key variables to estimate the cumulative uncertainty in each of the scenarios.

- **Step 6: Net Costs of Climate-Induced Weather Pattern**. An overall assessment of the scenarios was made, highlighting the present value of the economic value at risk due to climate change.

3.1 STEP 1: HAZARD, VULNERABILITY AND ASSETS-AT-RISK

3.1.1 Screening Assessment

The TCWR is located in an area of continental polar climate characterized by long cold winters. Daily winter temperatures often fall below –30°C, and during the short cool summers temperatures can reach 25°C (EBA 2001). Precipitation is sparse, with approximately half falling as snow. Prevailing winds are from the east and average 15–17 km/hour. They often cause blowing snow, which can be a problem for road operations (EBA 2001). Major storms with high winds and blowing snow can cause temporary closures on the road, such as the storm documented in March 2012 that caused a multiple-day road closure and subsequent road clean-up (Rodan 2012). Storms such as the March 2012 event can endanger drivers because they provide an incentive to reach a camp before the storm worsens, although some drivers end up waiting out storms on portages (Rodan 2012). These unforeseen temporary road closures can delay the road closing date if loads need to be hauled to the camps before the end of the season (Rodan 2012). This implies that season closure dates for the TCWR may be influenced by operational needs.

Trucks moving on the ice create waves of water under the ice surface, which causes it to flex. Trucks driving over the wave can result in the ice breaking open, an event called a blowout (Ashbury 2006). Blowouts can cause the road to be shut down for maintenance and, depending on severity and timing, bring the risk of permanent closure. Limiting speeds and mandating minimum spacing between trucks reduce the number of these ice blowouts. The roads are built with S-curves at the portages to help limit speeds where the ice meets the shore. The road is particularly vulnerable at these portage connections. Pressure ridges and cracks can be bridged by steel ramps that vehicles travel on, which can avert road closure.

The JVMC has identified climate change and winter warming trends as a concern for the longevity of the ice road (Greenspan 2008). Although 2007 was a record high year for loads, 2006 was one of the worst years and led the mine owners to start considering alternatives to the ice road (Sherk 2007; McGregor, Hassan and Hayley 2008). The 2006 season opened late and closed after only 49 days of operation because of unsafe ice conditions. The result was that approximately 1,200 loads had to be flown into the mines in the summer and fall of 2006 at great expense to the mining companies (JVMC 2013). Climate trends and their implications for winter roads are further analyzed in Appendices A and B.

Following the short 2006 winter road season, a number of the short-term strategies mentioned earlier were implemented that enhanced operations: (i) improved techniques for assessing ice capacity and locating discontinuity using improved radar systems; (ii) traffic management through express lanes to separate loaded trucks from returning trucks, allowing the speed restrictions on the returning trucks to be relaxed; (iii) implementation of multiple routes across lakes with known ice instability to allow rapid traffic redirection in the event of ice deterioration; (iv) greater vigilance over speed restrictions, together with driver awareness campaigns; (v) flooding ice roads and ice bridges to increase ice thickness and delay the closing date; (vi) plowing snow off the road alignment; and (vii) restricting hauling to darkness hours during warmer periods (McGregor, Hassan and Hayley 2008; Rawlings, Bianchi and Douglas

2009). Building multiple routes has been identified as a key strategy for the TCWR and flooding has been used with increasing frequency.

Similar short-term strategies have been employed on other winter roads. Spraying ice roads is an alternative to flooding that is used frequently. Building a permanent bridge over road choke points such as lakes and streams is another technique that has successfully extended the season of other winter roads (Rawlings, Bianchi and Douglas 2009).

The climate analysis in Appendix A compared available climate data against operating season length and found that the strongest indicator for longer seasons was the accumulation of freezing-degree days, a winter temperature variable. Freezing-degree days have decreased significantly over the past decades, indicating a tendency towards reduced ice thickness and a shorter winter road season. Changes to road construction methods have mitigated that outcome. The decrease in freezing-degree days has resulted in increased efforts to maintain ice thickness and prolong the season. Projections indicate that this decrease in freezing-degree days will continue. Other climate variables, such as amount of snowfall and rapid temperature increases or decreases, were also investigated, but found to have less significance. Snowstorms are less of a concern for the TCWR because there is a lot of equipment to maintain the road and clear snow, but other winter roads may be more vulnerable to early-season snowfalls. If the snow is not cleared in a timely manner, it may have enough of an insulating effect on the ice to end the season.

Despite a prediction that the road would be viable for several decades (Natural Resources Canada 2013), based on historical trends and projections of future climate change, changes in ice road sustainability are likely. Freezing-degree days and melting-degree days will affect the length of the season (Appendix B). Other research in the region is looking at historical temperature trends, lake sediment cores and climate projections to get a better sense of how climate change might influence the viability of the road (Galloway et al. 2010; Natural Resources Canada 2013).

3.1.2 PIEVC Hazard Assessment

Hazard analysis identifies a specific set of circumstances that could potentially result in a negative outcome. A hazard is a specifically defined interaction between a climatic event and a component, or components, of a piece of infrastructure being studied. Using the PIEVC protocol, climatic events were identified that could occur in the region within the time horizon (to the 2050s) of the vulnerability assessment. These events were then applied against the infrastructure components forming the TCWR to test how they would react; this identified a set of hazards. The hazards were then ranked based on variables such as likelihood and severity, which allowed a calculation of values at risk due to climate-derived events.

The PIEVC assessment considered 23 climate parameter/threshold combinations and 32 infrastructure components, yielding a total of 736 possible interactions. In consultation with experts and technical advisors through interviews and a PIEVC workshop, 96 major climate/infrastructure interactions were identified. These interactions form the core of the risk assessment and are categorized according to severity:

- 12 high-risk interactions;
- 53 medium-risk interactions; and
- 31 low-risk interactions.

Risks were generally associated with five aspects of the TCWR:

1. **Road operations**. Road operations are vulnerable to climate conditions that could result in load and service interruptions. While these interruptions can be made up through road management practices in the early or mid-season, there may not be sufficient operational management flexibility to recover if they occur later in the season.

2. **Rapid temperature change: ice surface**. Although rapid temperature change (greater than 18°C in a 24-hour period) was considered to be a potential risk, subsequent climate analysis indicated that rapid temperature changes are already being managed on the road and that the probability of such events will slightly decrease over the time horizon of the assessment. Therefore, rapid temperature changes were not considered to be a significant climate change risk.

3. **Pre-season snowfall: portages**. Lack of pre-season snowfall can affect the preparation of portages and ramps along the route. If the snow used to establish the portage roadbed is in short supply, this will prolong preparation times and delay the opening of the road.

4. **Pre-season snowfall: thin ice**. An abundance of pre-season snowfall was determined to be a significant risk driver. Too much early-season snowfall can affect the rate of freezing of the ice sheet. In addition, snow that covers thin ice represents a significant safety hazard to crews preparing the road. Layers of snow can obstruct a clear view of thin ice, resulting in machinery and personnel breaking through the ice surface.

5. **Days above freezing: multiple infrastructure components**. More frequent periods of prolonged temperatures above freezing during winter operations could result in load and service interruptions on the road.

3.1.2.1 Road operations

In most areas, risks related to the normal road operation elements of the infrastructure assessment. Since the operators accommodate for severe weather by adjusting operational times, events that affect operational times tend to be a high priority. Events that reduce the number of operational hours in the year can be important. Fortunately, the road is operated based on total tonnage in a season and to date there has been sufficient flexibility in scheduling in most years to accommodate changes in the operational season.

The winter of 2006 was an exception. The road experienced a blowout midway on Waite Lake, which has an extremely rough bottom and many small islands and shoals (D. Hayley, pers. comm.). The location that closed the road was between an island and the shore, where the road passed over a shoal. In other locations the water under the ice was deep, but in this spot it was only 30–40 cm deep. Despite slow speed limits, a hydrodynamic wave caused the blowout (D. Hayley, pers. comm.). This happened fairly late in the season (March 14), which meant that an alternate route could not be established. A significant amount of the seasonal hauling had not yet been done and approximately 1,200 loads could not be delivered by the end of the season. Participants in the hazard assessment workshop reported that the early closure of the TCWR that year resulted in incremental costs between $100 and $150 million and contributed to the temporary closure of the Jericho Diamond Mine in 2008 (it was sold in 2010 and reopened briefly in 2012).

Of the 23 climate/threshold parameters initially identified by the assessment team, 7 were ultimately removed from further analysis as they were deemed to be insignificant risk drivers in relationship to road operations. Of the remaining 16 climate/threshold parameters, 11 yielded medium- or high-risk scores for road operations. Based on this analysis, road operations were found to have relevant risk interactions for roughly 70% of the climate parameters considered.

Generally there is sufficient flexibility in road operation scheduling to accommodate service interruptions. Interruptions that are sufficiently severe, particularly late in the operating season, can result in significant economic loss, as demonstrated during the 2006 season. For this reason, road operations dominate the risk profile for the TCWR. Increasing the annual tonnage targets for the road, while at the same time attempting to reschedule road operations around more frequent climate-driven service interruptions, could exacerbate these risks.

3.1.2.2 Rapid temperature change/ice surface

The screening assessment identified rapid temperature change as a risk to road ice surface. Rapid changes can trigger cracking in the surface ice sheet, which compromises the road's structural integrity. Consecutive days where these events occur increase the risk to the road ice surface.

A climate parameter was developed that considered up to 20 consecutive days with rapid temperature changes. It was established that these events already occur in the baseline climate forecast and that they will likely decrease in frequency, if only slightly, over the time horizon of the assessment.

These observations led to the conclusion that rapid temperature changes are currently being managed by the JVMC and that the overall risk associated with rapid temperature changes over the time horizon of the assessment will decrease based on the current and future climate profile.

3.1.2.3 Pre-season snowfall/portages

Workshop participants identified high risks associated with the impact of pre-season snowfall on portages. The road construction teams use early season snow to establish roadbeds through the portages and to build ramps. A lack of early season snowfall can prolong the construction period, as teams wait for sufficient snow to accumulate or are forced to move snow from lakes onto the portages. This can delay the opening of portages, resulting in a shorter overall operating season.

Given their associated risks, portages can be a vulnerable element of the ice road. The amount of pre-season snowfall needs to be within a normal range to prevent unfavourable outcomes. Deviations from this range can result in operational delays; as discussed in the section on road operations, these are significant to the overall TCWR risk.

3.1.2.4 Pre-season snowfall/thin ice

Too much pre-season snowfall can also contribute to increased risk. The screening assessment identified that too much snow in the early season slows ice thickening. Too much snow can hide structural issues with the ice (both structural and surficial) and obscure the ability of workers and equipment to detect hazards or thin ice, thereby contributing to safety risks. Historical observations indicate that too much pre-season snowfall contributed to a hazardous event during the construction phase of the 2003 road. Amphibious vehicles equipped with ground-penetrating radar are now used to reduce risk while determining ice thickness.

Climate analysis indicates that periods of significant pre-season snowfall are likely to occur during the horizon examined by this report. Since these events are highly likely, and since the consequence in the worst case could be loss of life, they are deemed to be high risk. Although pre-season snowfall has implications for delays in road operations, it is first and foremost evaluated for its potential effects on worker safety.

3.1.2.5 Days above freezing/multiple infrastructure components

A pattern of risk associated with days above freezing during the operating season was identified through the analysis. Two threshold values were identified as being relevant:

- 0°C for three consecutive days; and
- 0°C for five consecutive days.

While no high-risk interactions were observed for these thresholds, 44 medium-risk interactions were identified. As might be expected, risk scores were slightly higher for the five-consecutive-day threshold, but both threshold values yielded a pattern of risk.

Prolonged periods of temperature above freezing could result in reductions in loads and service. Operations might be possible only at night. Extended periods of above-freezing temperature could shut down sections of the road. Late in the season, with longer days, temperatures above 0°C for even fewer than three consecutive days can cause quickly deteriorating conditions, resulting in a temporary closure or a switch to night-time only use (R. Zschuppe, pers. comm.). Consecutive days with above freezing temperatures are already occurring and, with climate change, the team is projecting that it will be seen more often in the future.

Interactions have been observed in relation to multiple infrastructure components, with several medium-risk components:

- ice surfaces;
- ice bridges;
- portages;
- vehicles;
- secondary spur roads; and
- road operations.

From this analysis, a general pattern of risk to the road is anticipated based on prolonged periods of temperature above freezing. While much of this risk can be absorbed through flexible scheduling, the days-above-freezing variable has the potential to drive high levels of risk if there are enough of such days to significantly reduce the operating season.

3.1.3 Adaptation Responses

During the PIEVC assessment interviews and the workshop, experts discussed a number of possible adaptation measures. Throughout the workshop, participants emphasized the importance of flexible scheduling as a means of responding to climate fluctuations. For the most part, this practice can result in minimal cost increases while achieving operational goals despite service interruptions.

As indicated above, the JVMC has already invested in technologies to optimize the operability of the winter road system, which in some years operates near or at capacity (McGregor, Hassan and Hayley 2008). Initial economic studies by Babson College (2011) indicate that these construction and maintenance techniques and technologies can lengthen winter road seasons, saving between $6 million and $27 million a year in transportation costs. In the future, however, such techniques may not be as effective. Climate change may reduce the operational season for the road, resulting in less ability to reschedule. Additionally, the potential for new mines in the region or increased annual tonnage requirements could further compromise scheduling flexibility. Indeed, the initial modelling by Babson College indicated that in the future the TCWR may fail to deliver sufficient supplies in some winters and that the additional cost for each failed year increases over time. The Babson study concluded that given the effects of climate change future operations may require alternative transportation methods (Babson College 2011).

Nevertheless, in the short term, flexible scheduling is a bridge between the current mode of operation and other more robust adaptation measures. As part of this bridging strategy, it will be important to focus on key maintenance and operational practices, including monitoring of the road components and weather, and ongoing analysis of climate projections for the region. The road operators are already applying these processes, so there should be minimal financial costs associated with continuing and enhancing these activities.

Other, more robust adaptation measures were discussed by workshop participants:

- **Construction of permanent bridges**. One expert proposed the use of permanent bridge structures as an adaptation for ice roads; these would be used only during the winter road operational period. Workshop participants indicated that there are no river crossings on the current TCWR alignment. Thus, this adaptation measure may not be relevant in the present analysis. However, it may be viable for other ice road applications.

- **Construction of permanent road alignments on portages**. Some experts suggested that building permanent road alignments on portages would be a potential adaptation measure. In this scenario, permanent roadbeds would be prepared, but used only when the ice road was in service. This would eliminate the sensitivity to early season snowfall and allow road operations to commence as soon as the ice sheet was deemed safe. Permanent road padding, made up mostly of esker sand, has already been put in place in some sections.

- **Construction of permanent all-season roads**. If winter road operations become seriously affected by changing climate conditions, some of the experts suggested a permanent all-season road. This option could be built in phases, constructing permanent all-season roads where feasible and connecting with ice roads during winter operations where necessary.

The construction of an overland route — along with construction of a deep sea port and bringing in power lines to reduce fuel needs — were some of the large-scale adaptation responses that the JVMC considered in 2007, among many other potential options. The cost, time frame and environmental issues of each option were analyzed to identify the most realistic alternatives (Finlayson 2007).

Three final concepts were considered, all of which would take approximately five years to implement and all of which were expected to be very costly. In 2007, when these concepts were being considered, annual loads were projected to increase up to 14,000 t, which would likely be more than the existing road could handle (Finlayson 2007; Sherk 2007).

- **Construction of a seasonal overland route**. This would parallel the TCWR along its most southern portion. This is the section that melts earliest and was the source of most of the 2006 difficulties. The new road would be a gravel-surface route, built on a base of shot rock fill — a foundation of broken stones often used in water or on soft ground — with a smooth gravel layer on top, and covered by compacted snow. Travel on the road would not be permitted until the snow base had been built up to protect the fill material.

- **Construction of a deep sea port**. Another proposed option was to build a road from a deep sea port at Bathurst Inlet; the port has been proposed, but not yet built. This option would benefit Nunavut, provide a route for base metals as well as diamonds, and be another way for the federal government to exert Canadian sovereignty in the Arctic.

- **Bringing in power lines**. The third alternative was to build 600 km of power lines from the Taltson hydroelectric station near Fort Smith and expand the station’s production. This would reduce the reliance of the mines on diesel power, and since diesel is the main good transported to the mines, this would greatly minimize loads.

The construction of a seasonal overland road as an adaptation option along the southern portion of the road was reiterated in the expert interviews following the PIEVC workshop. The Government of the Northwest Territories (GNWT) has recently revived its interest in constructing a southern overland road to the Lac Des Gras area of the NWT (Quenneville 2015a). The GNWT is considering financing options for an all-weather road to improve transportation access into the Slave Geological Province (SGP) to better support diamond mining operations and to encourage new mineral exploration and mine development in this mineral-rich region.

Investment in extending the NWT's all-weather road system into the SGP would significantly reduce transportation-related costs to operating mines and extend mine life. It would limit the effects of climate change to spur ice roads to mining installations (if construction of such spur roads is continued under an all-weather access model). It would also significantly reduce the annual cost of constructing and maintaining winter roads that serve mining-related projects in the NWT and western Nunavut. An all-weather road would not eliminate all climate change risk, since climate still influences roadways, but it would reduce significantly affect the operating and cost implications of relying on seasonal, ice road access (P. de Bastiani, Assistant Director of Planning, GNWT Department of Transportation, pers. comm.).

3.2 STEP 2: CLIMATE CONDITIONS AND FORECAST

This step in the methodology aims to quantify the economic implications of projected climate trends on the TCWR's operation and use. This will inform the rationale for some of the more robust adaptation measures that are being considered.

These climate variables were identified as important through the PIEVC workshop and further climate analysis undertaken by Risk Science International in relation to the economics of the TCWR:

- operational season length (interaction of freezing-degree days and melting-degree days);
- incidence of temperature swings in excess of 18˚C;
- incidence of consecutive days above 0˚C during the operational season;
- amount of snow on the ground January 1; and
- number of extreme cold events during the operational season.

Projections for these variables' future expected values and their associated probability distributions are presented in Figure 2. Estimates for these climate variables are drawn from the RCP8.5 scenario in the Intergovernmental Panel on Climate Change (IPCC) assessment reports (IPCC 2013).

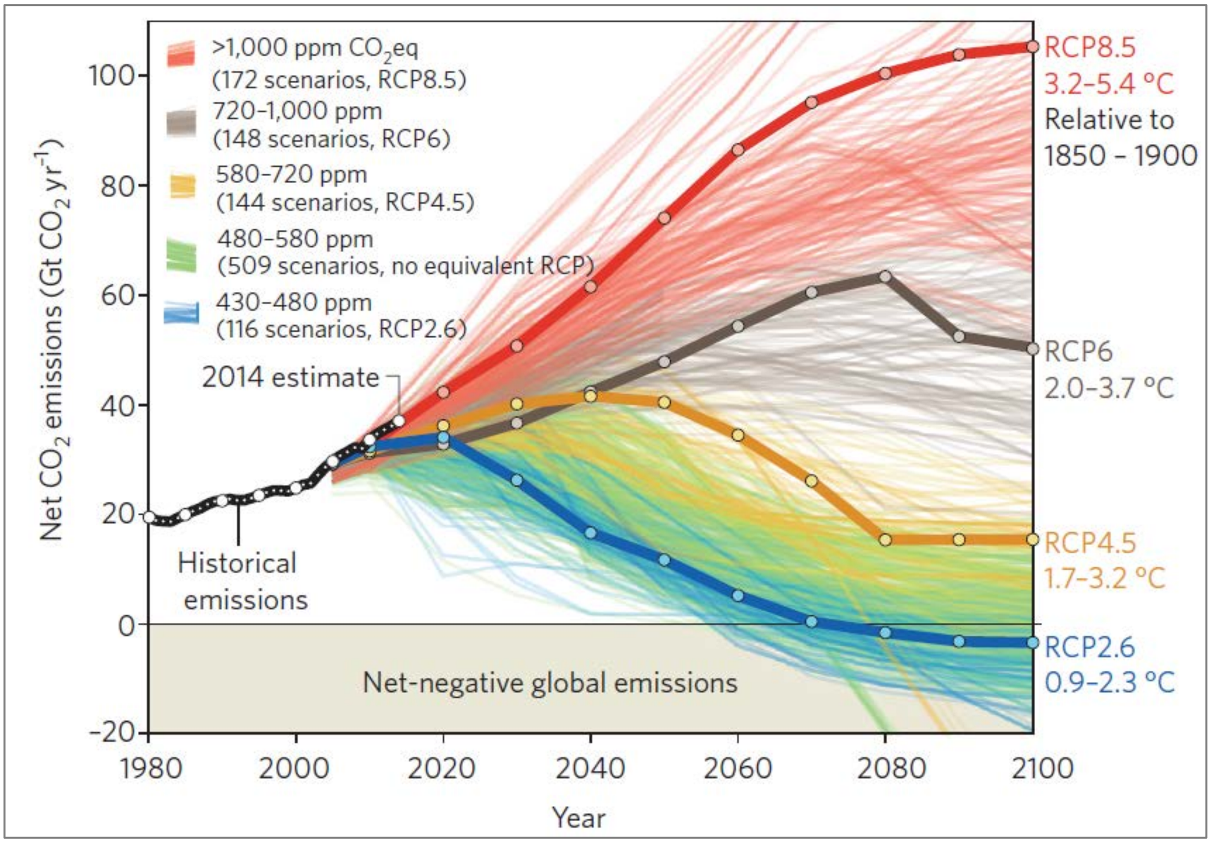

Figure 2: Emission projections from IPCC modeling

Source: Fuss et al. 2014

Perhaps the most convincing argument for the use of RCP8.5 climate scenarios in the projection of relevant climate variables for this project, versus RCP4.5 or RCP6 or the blending of scenarios, is that based on historical trends, the planet is definitively following the RCP8.5 pathway, a trend that has continued in the 2014 data. In addition, given the lack of binding international agreements on greenhouse gas (GHG) emissions and the atmospheric persistence of GHGs (hundreds of years), present trends are unlikely to be reversed between now and 2050. Therefore the RCP8.5 level of climate change is a reasonable expectation for the study period.

There have been recent indications that a global GHG agreement may be possible by 2020. The United States and China have recently announced a bilateral agreement that they hope can lead to a global agreement. When examined closely, however, the proposed commitments are not at a level that would alter projections for the 2050s. For this reason — and because of the need to engineer TCWR road infrastructure to be risk-resilient — the projections below are consistent with the RCP8.5 scenario.

Estimates are provided for climate variable values in the 2020s and 2050s. For the purpose of calculations, a linear trend line between the two periods was applied, since such a trajectory is consistent with the projected evolution of variable values.

In terms of these variables' probability distributions, the preferred approach would be to apply historic distributions to estimates of future viability and then add to this an additional standard deviation factor associated with the range of future climate change projections. However, this second step cannot be easily accomplished without applying a 24-hour time period to the calculations in the climate models, which were carried out monthly or seasonally. Therefore, in order to account for the added uncertainty in estimates of future climate conditions, the relative magnitude of the range in variables' values that has been historically observed has been taken as the range for climate variables' future distributions. In terms of the probability distribution within this range, a normal distribution is used; it applies the same standard deviation that was experienced historically, but as a proportional share of the given time period's expected value.

3.2.1 Projected Climate Variables

3.2.1.1 Operational season length

A possible correlation was evaluated between warm early seasons and warm road seasons overall to better understand the impact of temperature on operational season length. This was done by taking the average of all December to January (Dec–Jan) mean temperatures from 1943–2013 and the average of all December to March (Dec–Mar) mean temperatures for the same years. Each year's value was then compared to the mean to see if it was a positive anomaly (warmer than average) or negative anomaly (colder than average). The results clearly indicated that if the Dec–Jan period was colder than normal, the entire season was colder than normal and if Dec–Jan was warmer than normal, the entire season was warmer than normal. This can be seen in Figure 3, where positive anomalies and negative anomalies per year are almost always synchronized. This implies that most of the time (61 of the 71 years calculated, or 86% of the years); the Dec–Jan temperature is a good indicator of the entire season (Dec–Mar) temperature. The ten years where the Dec–Jan and Dec–Mar temperature anomalies did not match were 1948, 1955, 1967, 1968, 1977, 1978, 1979, 1984, 2005 and 2008. In most of these non-matching years, the anomalies were still close to agreement.

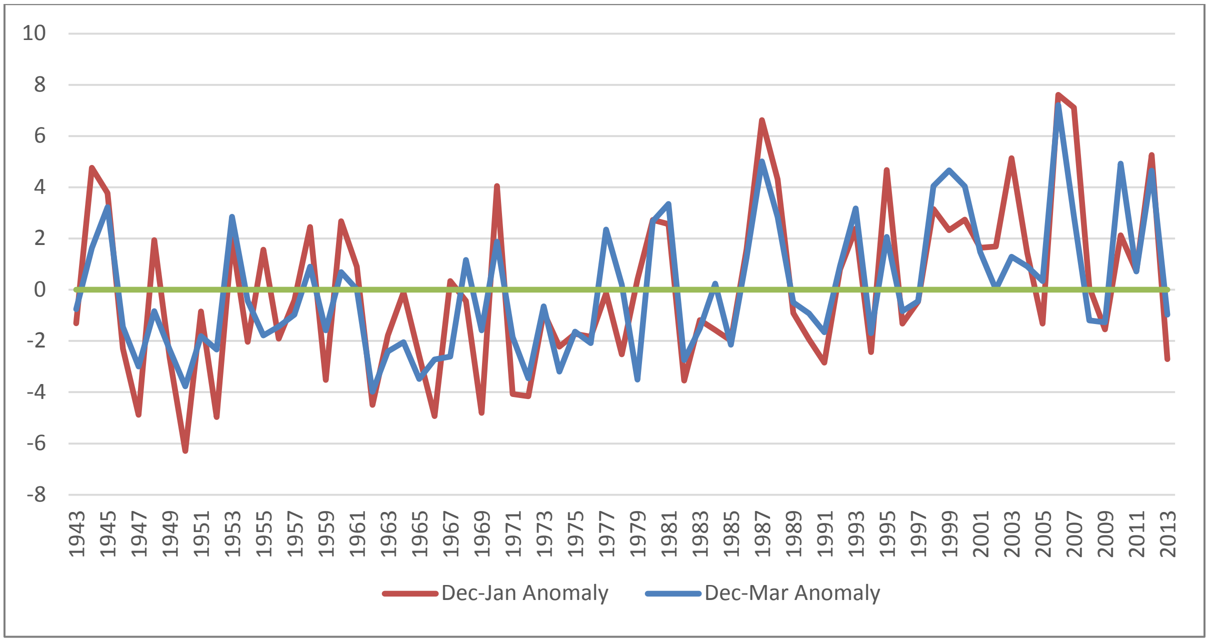

Figure 3: Correlation between warm early season (Dec–Jan) and warm road season overall (Dec–March) using mean temperature anomaly at Yellowknife A

Data source: Environment Canada 2014

Under historical climate conditions, the TCWR is generally resilient. However, the road may not be as resilient over the assessment time horizon of the 2020s and 2050s (Table 1). Over these periods, the average operating season duration may be reduced to 41 days. An exceptionally warm year during a period with an average season length of 41 days could easily reduce the operational season to around 30 days, based on the forecast climate analysis. This situation could lead to increased difficulties in applying the flexible scheduling methodologies currently used and could result in failure to meet annual tonnage targets. Table 1 compares the historic and projected operational season lengths (JVMC 2013) based on the climate analyses in Appendices A and B.

Table 1: Operational season length (days)

Time Period	Value/estimate (Number of days)	Range (Number of days)	Standard Deviation
1981–2010	65	47–78	+/–8
2020s	58	44–72	+/–7
2050s	49	37–61	+/–6

3.2.1.2 Incidence of temperature swings in excess of 18°C

Temperature swings are not expected to become more or less prevalent over the forecast period. Their probability distribution is also expected to remain unchanged from the historical average (Table 2).

Table 2: Incidence of temperature swings in excess of 18°C (events per season)

Time Period	Value/estimate (Events/season)	Range	Standard Deviation
1981–2010	31	18–55	+/–10
2020s	31	18–55	+/–10
2050s	31	18–55	+/–10

3.2.1.3 Incidence of consecutive days of temperatures above 0°C during operational season

The likelihood of consecutive days of ice-melting temperatures during the operational season is expected to increase significantly over the forecast period. Such events are sufficiently rare that even with this increased likelihood the expected incidence is still fairly low, with only one three-day consecutive event expected during the operational season by the 2050s. Probability distributions were not available for these figures; therefore, a range and standard deviation of zero was applied (Table 3).

Table 3: Number of consecutive days > 0°C, November 1–April 1

Time Period	Three-day consecutive days >°C			Five-day consecutive >°C		
	Events/year	Range	Standard deviation	Events/year	Range	Standard deviation
1981–2010	0.10	0	0	0.00	0	0
2020s	0.27	0	0	0.03	0	0
2050s	1.13	0	0	0.40	0	0

3.2.1.4 Snow on ground January 1

The amount of snow on the ground January 1 affects both ice formation and safety considerations when constructing the winter road and the feasibility of portage construction. It is projected to decline slightly over the study period (Table 4). The impacts of this variable will be felt more in portage construction, since it requires snow.

Table 4: Snow on ground January 1 (cm)

Time Period	Value/estimate (cm)	Range (cm)	Standard Deviation
1981–2010	28.2	4–61	+/–10.5
2020s	23.8	0–51	+/–8.9
2050s	20.9	0–45	+/–7.8

3.2.1.5 Incidence of extreme cold events during operational season

The incidence of extreme cold events is expected to decrease significantly over the forecast period (Table 5), meaning that costs associated with coping with extreme cold will likely fall over time.

Table 5: Incidence of extreme cold events (<–35°C) during the operational season

Time Period	Value/estimate	Range	Standard Deviation
1981–2010	24.27	4–50	+/–11.3
2020s	16.17	1–31	+/–7.5
2050s	6.37	0–12	+/–3

3.3 STEP 3: ASSESSMENT SCENARIOS

Based on the vulnerability assessment and the detailed climate data that was assembled, two scenarios were identified that guided the analysis:

1. **Operations can adapt to a changing climate (adaptive scenario)**. In this scenario, increasingly difficult climate conditions lead to shorter operational seasons and steadily increasing maintenance and repair requirements to maintain road service levels. Road operations remain functional through adaptive measures.

2. **Operations are disrupted due to a changing climate (critical conditions scenario)**. In this scenario, highly challenging climate conditions lead to significantly increased costs due to the late opening and/or early closure, or non-opening, of the TCWR.

These two scenarios capture the two basic outcomes possible under increasingly difficult climate conditions on the TCWR: operation and maintenance become more difficult and costly; or the desired levels of road availability become impossible, necessitating the use of alternative transportation measures or making it impossible to move some loads altogether.

Thresholds for the climate variables outlined above were identified through consultation with stakeholders. This information indicated which specific kind of climate conditions, and what type of interactions between these conditions, would be associated with each of the two scenarios.

3.4 STEP 4: ECONOMIC ASSETS-AT-RISK AND FORECASTS

This step links the detailed climate analytics with the likely costs that are expected under the two assessment scenarios. The approach uses welfare economic principles[2] to estimate the incremental economic costs under each scenario, all of which are estimated using Monte Carlo analysis to factor for variable uncertainties. A Monte Carlo analysis is commonly used to model phenomena with significant uncertainty. Probability distributions were used for all key variables to estimate the cumulative uncertainty in each of the scenarios. All key input parameters are expressed as probability density functions. More technical detail on the approach and methods can be found in Sawyer 2014.

The focus of this step is to identify the significant costs, estimate their magnitude and associated uncertainty, and link them with the relevant climate variables. The objective is to understand how changes in climate variables are expected to drive changes in cost variables. (Step 5 extends this analysis in order to establish exactly how and why costs are affected.) Implicit in Steps 4 and 5 is the development of a damage function, an equation that specifies the relationships between costs and climate variables and thereby establishes how much economic cost is associated with a given change in one or more climate variables.

Data collection on economic assets at risk was undertaken through a combination of a literature review, interviews and surveys with road operators and users. Literature on ice roads was reviewed to develop estimates of the various costs considered in this analysis and these costs were verified or discussed by participants in the PIEVC protocol workshop and other TCWR stakeholders. Phone interviews were conducted with a range of stakeholders, some of whom received a follow-up questionnaire that asked them to provide background information, cost figures and estimates of likely cost impacts under current and worsening climate scenarios.

Table 6 provides an overview of variables that were found likely to trigger economic costs under various climate scenarios. These costs form the basis of developing the economic losses associated with a changing climate.

[2] Welfare economics uses microeconomic techniques to evaluate well-being at the economy-wide level. It provides the basis for public economics and tools such as cost-benefit analysis.

Table 6: Cost impacts triggered by a changing climate

Cost variables	Description	Impacted stakeholder(s)
Flexible scheduling costs (shorter season)	Logistical costs and personnel and capital costs associated with coping with a late start and/or early end of the operational season	Carriers
Flexible scheduling costs (interruptions to operations)	Logistical costs and personnel and capital costs associated with interruptions to road availability during the operational season	Carriers
Ice thickening or repair measures (flooding and sanding)	The costs of thickening ice, either to build up an insufficient amount or to build up ice on sections that are in need of repair	Road operators
Increased ice road construction and maintenance costs	The increase in ice road construction and maintenance costs due to changes in climate conditions during the operational season	Road operators
Increased portage construction and maintenance costs	The increase in portage construction and maintenance costs due to changes in climate conditions during the operational season	Road operators
Increased ramp construction and maintenance costs	The increase in ramp construction and maintenance costs due to changes in climate conditions during the operational season	Road operators
Safety-related costs associated with working on thin ice	The cost, over and above the baseline, of safety-related responses to the need to work on thin ice	Road operators

Cost variables	Description	Impacted stakeholder(s)
Safety and equipment failure costs dues to extreme cold	The cost, over and above the baseline, of safety-related responses and equipment failures associated with an increasing incidence of -40°C temperatures	Road operators
Modal shifting	The cost associated with the use of alternative transport measures when the winter road season is not sufficient to meet demand	Mines
Production loss	Lost economic value associated with production that did not occur due to an inability to transport needed supplies and equipment during a season	Mines

As mentioned above, estimates of the magnitude of the climate-driven changes in these cost variables were developed through surveys, interviews and a literature review. Table 7 provides an overview of the cost parameters used in the analysis, which are summarized using minimum, central and maximum values. In some cases a minimum and maximum value were identified directly; in other cases, an assessment of the range of uncertainty associated with the central figure was used to develop the minimum and maximum values. When uncertainty information was unavailable, qualitative uncertainty estates were assigned quantitative uncertainty ranges: a variance of either +/– 5%, 15%, or 40% around the central value was applied to estimates with low, medium, and high uncertainty, respectively. A triangular distribution[3] among minimum, central and maximum values was employed in the ultimate analysis.

Table 7: Cost parameter values used in economic analysis

Cost Variable	Units	Minimum	Central	Maximum	Source
Flexible scheduling costs (shorter season)	$/tonne-km	$0.07	**$0.12**	$0.18	RTL, Prentice, 2013

[3] A triangular distribution is a continuous probability distribution with a lower limit *a*, upper limit *b* and mode *c*; $a < b$ and $a \le c \le b$. It is used when the relationship between variables is known but data is scarce.

Cost Variable	Units	Minimum	Central	Maximum	Source
Flexible scheduling costs (interruptions to operations)	$/tonne-km	$0.03	**$0.06**	$0.09	RTL, Prentice, 2013
Ice thickening or repair measures (flooding and sanding)	$/hour	$550	**$650**	$750	Nuna Logistics
Increased ice road construction and maintenance costs	$/hour	$170	**$200**	$230	Nuna Logistics
Increased portage construction and maintenance costs	$/hour	$106.25	**$125**	$143.75	Nuna Logistics
Increased ramp construction and maintenance costs	$/hour	$63.75	**$75**	$86.25	Nuna Logistics
Safety related costs associated with working on thin ice	$/hour	$170	**$200**	$230	Nuna Logistics
Safety and equipment failure related costs due to extreme cold	$/hour	$63.75	**$75**	$86.25	Nuna Logistics
Modal shifting costs	$/tonne	$576	**$960**	$1344	Various sources
Production loss costs	$/tonne	$1350	**$2250**	$3150	Various sources

With the exception of costs related to modal shifting (using alternative transport measures when required loads cannot be transported via winter road) and production loss, all central estimates for the cost variables in Table 7 were collected via interviews and surveys. Flexible scheduling costs were estimated using a baseline estimate of northern ice road transport costs, which averaged $0.32 per tonne-kilometer (Prentice 2013). These and other cost-benefit analysis inputs and assumptions are summarized in Table 8. Where distributional information was not available for the figures seen in Table 8, the same 5%, 15%, and 40% variances were applied, based on the assessed level of associated uncertainty, and triangular distributions were again applied in the ultimate analysis.

Table 8: Inputs and assumptions used in economic analysis

Cost Variable	Units	Minimum	Central	Maximum	Source
Ice road transport cost	$/tonne-km	0.272	**0.32**	0.368	Prentice 2013
Alternative transport cost	$/tonne-km	1.92	**3.2**	4.48	Quenneville 2015b
Average distance traveled	km	255	**300**	345	Estimated
Average load tonnage	tonnes	27.58	**32.45**	37.31	JVMC 2014
Average seasonal tonnage	tonnes/season	120,020	**21,6643**	33,0002	JVMC 2014
Road length	km	380	**400**	420	JVMC 2014
Ice road length	km	323	**340**	357	JVMC 2014
Portage length	km	57	**60**	63	JVMC 2014
Number of portages	(no units)	61.75	**65**	68.25	JVMC 2014
Number of ramps	(no units)	123.5	**130**	136.5	JVMC 2014
Ice road repair time (1/4 of road length)	hours	340	**567**	793	Estimated
Total ice road construction time	hours	867	**1,020**	1173	Estimated
Total portage construction time	hours	1,530	**1,800**	2070	Estimated
Total ramp construction time	hours	663	**780**	897	Estimated

Costs due to modal shifting and production loss were estimated by examining the 2006 failure of the TCWR.[4] In that year, approximately 1,200 loads did not travel via the ice road (JVMC 2014). By examining TCWR road statistics from 2002–2012 it was determined that the average load during this time weighed 32.454 t (JVMC 2014); therefore, the weight of the 1,200 loads could be estimated at 38,945 t. The 2006 closure was estimated by road operators to have cost road users $100–150 million, so the central estimate of $125 million was divided by the estimated total tonnage of 38,945 for the 1,200 loads to produce an expected combined modal shifting and production loss cost of $3,210 per tonne (assuming an average distance traveled of

[4] This method was selected because no estimates or projections of future closure costs emerged from the project's interviews, survey or literature review. The historical experience was therefore determined to be the most reliable means of estimating potential future costs. Because of the uncertainty surrounding this estimate the maximum variance of 40% was applied.

300 km). This figure was then broken out into its component parts (both modal shifting costs and production losses) by assuming that alternative transport measures are typically ten times as costly (Quenneville 2015b) and by again assuming that the average distance traveled was 300 km. Based on these calculations, the cost of transporting the 38,945 t in 2006 by alternative means was estimated to be approximately $960 per tonne. The balance of the combined figure for modal shifting and production cost was then attributed to the production loss component, giving an estimate of approximately $2,250 per tonne for this figure. This method thereby estimates a 3:7 ratio between modal shifting and production costs.

With respect to interactions between cost and climate variables, Table 9 provides an overview of the climate variables identified as being relevant to road operation and use costs, the conditions under which they have an impact, the type of costs they incur and the stakeholders they affect under these conditions. The basis for many of these relationships and anticipated impacts emerged from the PIEVC workshop and from subsequent expert interviews. The effects of climate variables on road operation and use (and thereby costs) is discussed in detail in Section 3.2.

Table 9: Changing climate variables and affected costs

Changing climate variables	Impact scenarios and their defined thresholds	Affected cost types	Affected stakeholder(s)		
			Carriers	Road operators	Mines
Operational season length Operational season shortens due to interaction of the number of freezing-degree days and melting-degree days	**Adaptive Scenario** Threshold: Operational season <60 days	Flexible scheduling costs (shorter season)	✓	—	—
	Critical Conditions Scenario Threshold: Operational season <50 days	Modal shifting	—	—	✓
		Production loss	—	—	✓
Incidence of temperature swings in excess of 18°C Can lead to ice cracking and shifting, which compromises road's integrity	**Adaptive Scenario** Threshold: three or more incidences	Flexible scheduling costs (interruptions to operations)	✓	—	—
		Ice thickening or repair measures (flooding and sanding)	—	✓	—

Changing climate variables	Impact scenarios and their defined thresholds	Affected cost types	Affected stakeholder(s)		
			Carriers	**Road operators**	**Mines**
	Critical Conditions Scenario Threshold: Interaction with other conditions	Modal shifting	—	—	✓
		Production loss	—	—	✓
Incidence of consecutive days of above 0°C temperatures during operational season Prolonged periods of temperature above freezing during operational season, necessitating repair to sections of the road	**Adaptive Scenario** Threshold: two occurrences of two consecutive days or one occurrence of five consecutive days	Flexible scheduling costs (interruptions to operations)	✓	—	—
		Ice thickening or repair measures (flooding and sanding)	—	✓	—
	Critical Conditions Scenario Threshold: Interaction with other conditions	Modal shifting	—	—	✓
		Production loss	—	—	✓
Snow on ground January 1 – ice road impacts Too much snow on the ice in the early season slows ice thickening and can create safety concerns during ice road construction	**Adaptive Scenario** Threshold: More than 25 cm	Increased ice road construction and maintenance costs	—	✓	—
	Critical Conditions Scenario Threshold: Interaction with other conditions	Modal shifting	—	—	✓
		Production loss	—	—	✓
Snow on ground January 1 – portage and ramp impacts Too little pre-season snowfall can delay the opening of portages since ramps need snow for construction and	**Adaptive Scenario** Threshold: Less than 15 cm	Increased ramp construction and maintenance costs	—	✓	—
		Increased portage construction and maintenance costs	—	✓	—

Changing climate variables	Impact scenarios and their defined thresholds	Affected cost types	Affected stakeholder(s)		
			Carriers	Road operators	Mines
portages require sufficient snow to meet licensing requirements	**Critical Conditions Scenario** Threshold: Interaction with other conditions	Modal shifting	—	—	✓
		Production loss	—	—	✓
Incidence of extreme cold events during operational season Extreme cold of temperature below –40°C can have implications for worker safety and equipment function	**Adaptive Scenario** Threshold: More than eight occurrences	General increase in operational costs	✓	✓	—
	Critical Conditions Scenario *(*N/A)				

As discussed in Section 3.3, the adaptive scenario describes a situation in which increasingly difficult conditions are encountered, but where road operators and users can adjust under slightly higher costs. The critical conditions scenario describes a situation where the road is not able to meet the demand, despite adaptation measures. As seen in Table 9, a number of climate conditions are considered in the adaptive scenario. The critical conditions scenario is triggered only under circumstances that lead to an operational season that is historically unprecedented in its shortness. Table 9 shows how the scenarios are triggered by changes in various climate variables, and which costs are affected when climate scenarios are triggered. The specific magnitudes of these costs under various climate scenarios and conditions are described in Section 3.5.

3.5 STEP 5: CLIMATE RISK AND ECONOMIC VALUE ASSESSMENT

This step combines the outputs of the previous steps to produce an assessment of climate and economic value at risk. This is done by linking climate conditions and scenarios with specific cost impacts. Step 5 merges the climate risks with the knowledge of present costs and their expected increases if particular climate conditions worsen.

Tables 10 and 11 convey the specific increases to costs under the two types of climate scenarios: adaptive and critical conditions. Baseline cost data is also provided for context. For example, for flexible scheduling costs, the cost increment associated with a shorter operational season is $0.12 per tonne-km, which is over and above the baseline cost of $0.32 per tonne-km. The table shows the central values for each cost variable as summarized in Table 7; the analysis uses the probability distributions seen in Tables 7 and 8.

As seen in Table 10, an operational season of less than 50 days is taken as the threshold for an adaptive scenario. Respective snowfall-related thresholds for this scenario of less than 15 and greater than 25 cm were drawn from interviews. Other threshold values were for the most part determined by looking at what would be above the historical average. In all cases these thresholds are deviations from the norm that interview and survey respondents believed could be dealt with, but that in some cases would involve higher costs.

Table 10: Incremental costs under adaptive scenario climate conditions

Cost type	Climate threshold	Impact	Baseline	Incremental cost	Source(s)
Flexible scheduling costs (shorter season)	Operational season length <60 days	25-50% increase in transport costs	$0.32 per tonne-km	$0.12 per tonne-km	RTL, JVMC, Prentice, 2013
Flexible scheduling costs (interruptions to operations)	35 or more incidences of temperature swings in excess of 18°C	Marginal impact if temperatures < 0°C	$0.32 per tonne-km	Negligible	RTL, JVMC, Prentice, 2013
	Two or more occurrences of three consecutive days of above zero temperatures	10-25% increase in transport costs due to associated road operation suspensions		$0.06 per tonne-km	RTL, JVMC, Prentice, 2013
Ice thickening or repair measures (flooding and sanding)	35 or more incidences of temperature swings in excess of 18°C	Marginal impact if temperatures < 0°C	$550-$750 per hour, 0.1-0.2 km per hour	Negligible	Nuna Logistics
	Two or more occurrences of three consecutive days of above zero temperatures	Mid-season flooding operations triggered		$650 per hour, affecting ¼ of ice road length	Nuna Logistics

Cost type	Climate threshold	Impact	Baseline	Incremental cost	Source(s)
	Five or more incidences of extreme cold events during operational season	Costs at high end of baseline range		$100 per hour higher than average cost	Nuna Logistics
Ice road construction and maintenance	Snow on ground January 1 >25cm	Road construction costs at high end of baseline range due to safety concerns associated with heavy snow on thin ice formation	$750-$1,000 per hour, 0.33 km per hour	$125 per hour higher than average cost	Nuna Logistics
	Five or more incidences of extreme cold events during operational season	Costs at high end of baseline range		$125 per hour higher than average cost	Nuna Logistics
Portage construction and maintenance	Snow on ground January 1 <15cm	Portage construction costs at high end of baseline range due to need to use lake snow	$450-$600 per hour, 33 metres per hour	$75 per hour higher than average cost	Nuna Logistics
	Five or more incidences of extreme cold events during operational season	Costs at high end of baseline range		$75 per hour higher than average cost	Nuna Logistics
Ramp construction and maintenance	Snow on ground January 1 <15cm	Ramp construction costs at high end of baseline range due to need to use more lake snow	$1,400-$1,800 per hour, six hours per ramp	$200 per hour higher than average cost	Nuna Logistics

Cost type	Climate threshold	Impact	Baseline	Incremental cost	Source(s)
	Five or more incidences of extreme cold events during operational season	Costs at high end of range		$200 per hour higher than average cost	Nuna Logistics

An operational season length of less than 45 days was taken as the basis for triggering a critical conditions scenario (Table 11), since at that point the road would not be able to accommodate an average season's demand, even if road operators worked at their historical peak efficiency. A critical conditions scenario stemming from an interaction of climate variables was also specified; specifically, an operational season length of less than 50 days combined with more than two incidences of consecutive days of above zero temperatures, more than 25 cm of snow on the ground January 1, or less than 15 cm of snow on the ground January 1. This alternative scenario was specified to capture the risk inherent if a relatively short season combined with operational complications to produce an even shorter season.

Table 11: Incremental costs under critical conditions scenario

Cost type	Climate threshold	Impact	Baseline	Incremental Cost	Source(s)
Modal shifting	Operational season length <45 days	Short operational season window necessitates use of alternative transport cost	N/A (purely increment al cost)	$960 per tonne	Various sources (see Section 4.4)
	Interaction of conditions - temperature swings, above zero temperatures and irregular snow conditions	Interruptions to service due to adverse climate conditions necessitates use of alternative transport measures, such as airlifts		$960 per tonne	
Production loss	Operational season length <45 days	Short operational season window causes key pieces of equipment/infrastru	N/A (purely increment	$2250 per tonne	Various sources (see Section

Cost type	Climate threshold	Impact	Baseline	Incremental Cost	Source(s)
		cture to not be delivered	al cost)		4.4)
	Interaction of conditions - temperature swings, above zero temperatures and irregular snow conditions	Interruptions to service due to adverse climate conditions causes key pieces of equipment/ infrastructure to not be delivered		$2250 per tonne	

3.6 STEP 6: NET COSTS OF CLIMATE-INDUCED WEATHER PATTERNS

In Step 6, the net costs were estimated for each of the two scenarios by combining the estimates and the distribution of specific costs (see Table 7), specific climate variables (Section 4.2), and their interactions (discussed in Sections 4.4 and 4.5). The resulting net cost figures were broken down using the cost typology identified in Table 6. The results of this analysis are presented in Section 4.

4.0 RESULTS

The results of both scenarios are provided in Table 12. For the adaptive scenario, where the mines and the road operator conduct ongoing actions to adjust to varying climate change, the greatest cost results from adaptive scheduling on the part of carriers. To the extent that the season is shortened below the threshold of 50 days, additional costs are triggered as loads are shifted. In total, over the assumed 35-year time horizon, the total costs of the adaptive scenario are in the order of $55 million.

Table 12: Scenario results ($ millions NPV @ 4%: 35 years)

Adaptive scenario	20th percentile	Mean	80th percentile
Flexible scheduling costs (shorter season)	$28.45	$44.26	$58.64
Increased ice road construction and maintenance costs	$5.18	$5.77	$6.35
Increased portage construction and maintenance costs	$4.69	$5.26	$5.79

Adaptive scenario	20th percentile	Mean	80th percentile
Increased ramp construction and maintenance costs	$0.20	$0.28	$0.36
Total: Adaptive scenario	**$39.51**	**$55.57**	**$69.75**
Critical conditions scenario	**20th percentile**	**Mean**	**80th percentile**
Modal shifting	$2.72	$64.49	$111.81
Production loss	$6.03	$149.15	$263.22
Total: Critical conditions scenario	**$9.10**	**$213.64**	**$377.64**

Figures 4 and 5 show how this probability is distributed around the mean. As shown, the distribution is fairly tightly packed around the mean; however, a long tail of probability above the mean reflects uncertainty over the climate variables in the future. The probability that the actual value is greater than the mean of $55 million is in the order of 60%, with a maximum value of $155 million.

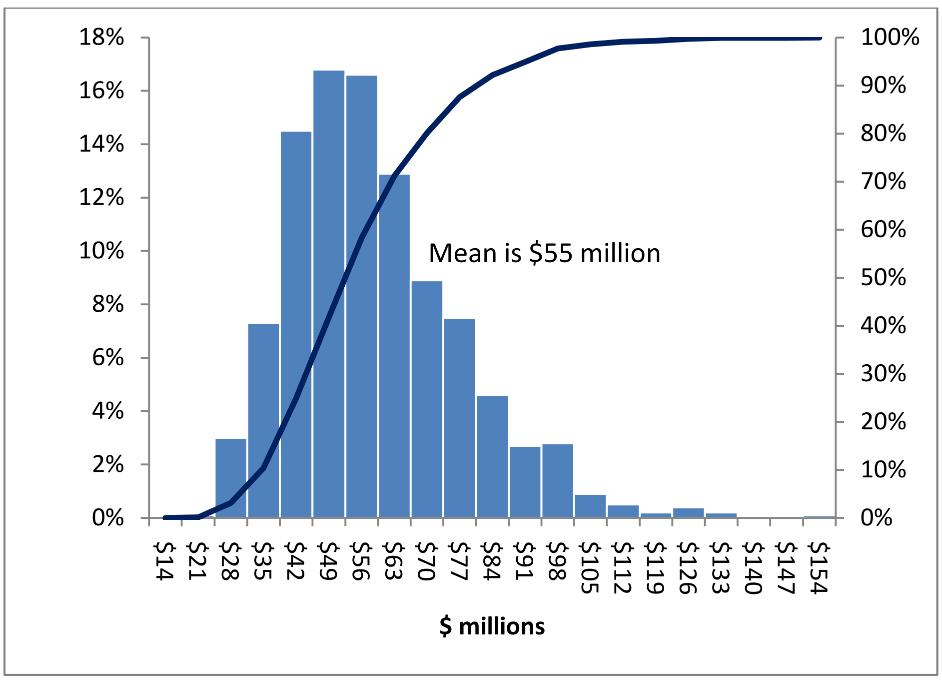

Figure 4: Adaptive scenario

For the critical conditions scenario (Figure 5), production loss dominates the expected total cost of $213 million. Modal shifting (the increased operating costs to get materials to the mines) at

$65 million represents about 30% of the total cost. The simulation reveals a significant tail above the mean, with 60% of the probability sitting above the mean and climbing to a maximum value of $1.8 billion. Small changes in the assumed forecast of operational season length have a significant impact on the results. This implies that the results are highly sensitive to this assumption of operational season length, and that small changes in the season length would result in large and significant future damages under the critical conditions scenario.

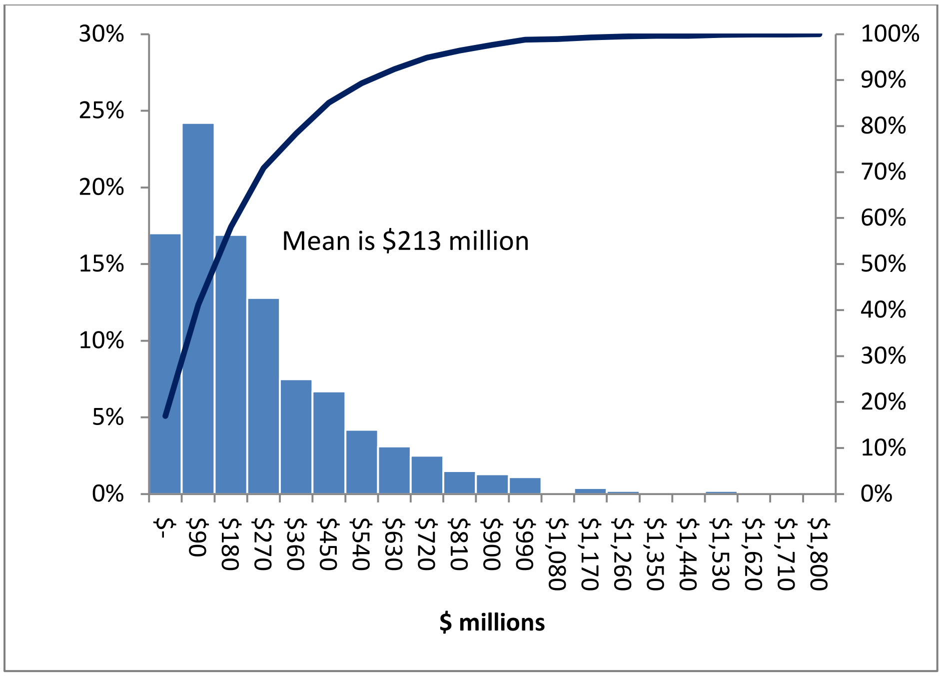

Figure 5: Critical conditions scenario

Of the climate variables, operational season length is the most important cost driver. This is partially because some climate-cost variable interactions that are identified as key risks from a cost perspective are likely to become *less* of a concern in the future. This is because the associated climate risks become less severe in the climate forecast. Extreme cold, for instance, is expected to become less pronounced over time. Other variables, such as the incidence of temperatures swings in excess of 18°C, are not expected to change significantly, which means they are not expected to drive any changes in baseline costs. The amount of snow on the ground January 1 is expected to decrease over the forecast period, meaning that risks exist only with respect to portage construction, and not for winter road construction. The incidence of consecutive days of above-zero temperatures is expected to increase over the forecast period, but not enough to trigger an adaptive scenario.

The lesser impact of some climate-cost variable interactions can also be explained by their relatively smaller incremental costs. For example, carriers' flexible scheduling costs are in the aggregate much more significant than road operators' construction costs, even when the adaptive scenario is triggered for both.

The length of the operational season is by far the most significant climate variable because of its significant impact on carrier costs in the adaptive scenario and its impacts on modal shifting and production costs for mines in the critical conditions scenario. This is a significant concern for the TCWR, since the length of the operational season is trending downward in the climate forecasts (averaging 49 days by 2050) and has a significant degree of annual variability. The results indicate that the expected evolution of the operational season length variable creates a significant economic risk to road users in the future if demand continues at the levels seen between 2002 and 2012. These costs would become even more pronounced if the demand for road transport increases.

5.0 CONCLUSIONS

Although the Tibbitt to Contwoyto Winter Road is likely to support ongoing operations for the mines that it now serves for a number of years, future climate variability and potential increases in demand for road transport could lead to the recurrence of events similar to those in the 2006 season.

With the development of the Gahcho Kué mine and other potential future projects in the area, road demand is likely to increase. The Gahcho Kué mine is planned to become operational in 2016, and therefore has a large number of shipments that need to be transported by winter road in the 2015 season. To date they have managed to move at least 75% of those supplies and will likely achieve the full 100% (Miller 2015). Miller (2015) notes that getting those shipments through before the end of the road season is at least partly the result of good planning by the company. Careful planning and flexible scheduling will help road users achieve the maximum use possible; however, it is important for users to understand the costs incurred due to flexible scheduling, and the costs that will be incurred if the season is shorter than the threshold for adaptation.

Currently, the impact of expanded use due to the Gahcho Kué mine is manageable, but if more projects are implemented there will be impacts on the ability of current mines to continue flexible scheduling and transport the required number of loads per season. Any future decisions around increasing the use of the road should take into account the possibility of shortened seasons.

The Government of the Northwest Territories is exploring options to build a permanent all-season road for the first half of the TCWR (Quenneville 2015a). This means that the most vulnerable sections of the road — the southern sections and the portages — may no longer be problematic. Construction of a permanent all-season road could extend the season by a month, or possibly longer (Quenneville 2015a). It could also significantly reduce the likelihood of triggering the adaptation scenario or crossing into the critical conditions scenario during the life of the current mine projects.

The TCWR is unusual compared to most other northern ice roads in that its main purpose is solely to supply mining projects. Although having a longer season would improve access for the TCWR, it is possible to move the required goods and equipment through flexible scheduling of loads in the existing operational season.

Most northern ice roads also service northern communities, or supply projects that require roads to be open as long as possible. In those cases, communities are concerned with having consistent road access for as long as possible, as opposed to achieving a certain number of loads. The lessons learned from the TCWR can inform those people making decisions for other ice roads on how to manage a road to extend the season as long as possible. The economic lessons from this report may not address the challenges faced by other ice roads, as flexible scheduling is not an adaptation that can be applied to all circumstances. For winter ice roads in areas currently at risk of warmer winters, building all-season sections in the most vulnerable areas may be the most viable solution.

Although shorter and warmer winters can be expected as a result of climate change, seasonal forecasting cannot yet predict with a high level of certainty when warmer winters will occur, or when temperature swings will be extreme enough to affect road operations. Managing the road with careful planning and preparation will allow road users to take advantage of flexible scheduling by shipping as early as possible to avoid the risks of a shortened season.

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APPENDIX A: HISTORICAL CLIMATE ANALYSIS

Tibbitt to Contwoyto Mining Road

Historical Climate Analysis

Prepared for:
Northern Climate ExChange (NCE)
Yukon Research Centre, Yukon College

March 31, 2014

A. 1 INTRODUCTION

The Tibbitt to Contwoyto Winter Road (TCWR) is a private winter road that services mining locations to the northeast of Yellowknife; it has been in seasonal service since 1982. Originally, the road was 600 km in length; it now ends around the 400-km mark. It consists of both lake crossings (87% of length) and portages (13%), which are intricately related to the yearly climate. The road season is primarily during the months of February and March and averages 67 days (JVMC 2013), although weather affects road construction and operations significantly from year to year.

Appendix A investigates some of the historical climate indicators that affect road construction and operation. The closest long-term climatological location is Yellowknife A (Yellowknife airport), which has climate data dating to 1942. A second location, with interpolated conditions, is located on Gordon Lake, northeast of Yellowknife. These locations, and the winter road route to Contwoyto, are discussed in more detail in section A.2.1.

This appendix identifies climatological relationships on a year-to-year basis, and compares them to operating days of the road for years for which data are available. Factors that show some major influence on operating season length are discussed, along with those that show little association. These factors are summarized in Table A13.

A.2 HISTORICAL CLIMATE FACTORS

Both temperature and precipitation are important to winter road construction. Temperature affects freezing, while precipitation in the form of snow or rain can affect the road in both positive and negative ways.

For most of the road length, data on these indicators are not available, so assumptions related to conditions at Yellowknife are used to generate climatological relationships. These relationships were then applied to interpolated conditions at Gordon Lake. The interpolated conditions were extracted from a Canada-wide dataset called CANGRD, produced by Natural Resources Canada and Environment Canada. The details of the CANGRD methodology for daily data can be found in McKenney et al. 2011. The relationship between observations at Yellowknife A and the Yellowknife CANGRD values were first evaluated to determine the CANGRD dataset applicability. The agreement provides strength for the use of this dataset at the interpolated location at Gordon Lake.

The climate factors considered for the winter road in this report are shown in Table A1. As shown, these factors can have either positive or negative effects on the road. The primary controller was expected to be freezing-degree day (FDD) accumulation, without which road construction cannot begin. These factors were evaluated on a yearly basis from the Yellowknife A daily observations. Road opening dates and season length information, where available, were measured against these factors. It is important to note that the opening date of the winter road is more likely controlled by climate than the closing date is. The road may be closed early if all required materials have been transported, even if it is still useable.

Table A1: Climate factors related to the winter road

1	Winter temperature	Colder — positive factor
2	Accumulated freezing-degree days (FDD)	Higher accumulation — positive factor
3	Accumulated melting-degree days (MDD)	Higher accumulation — negative factor
4	Date of accumulated FDD at 300 threshold	Earlier date — positive factor
5	Accumulated snowfall at January 1 (the sum of observed daily snowfall)	Higher accumulation — negative for the ice/lakes portion of the road, but positive for the land portion of the road. Since ice formation is critical, this is considered here as a predominantly negative factor
6	Snow on ground at January 1 (measured snow on ground)	As above – predominantly a negative factor
7	Accumulated rainfall in November and December prior to the winter road season	Higher accumulation — a negative factor, since it contributes to ice/snow melt
8	Days with a 24-hour temperature change greater than 18°C in November to April	Higher value — a negative factor, since it contributes to the formation of ice road cracks
9	Days with a mean temperature above 0°C in November to April	Higher value —a negative factor, since it contributes to ice/snow melt
10	Days with a 24-hour temperature drop greater than 20°C in November to April	Higher value — a negative factor, since it contributes to the formation of ice road cracks
11	Observed ice thickness (Yellowknife, Great Slave Lake)	Higher value — a positive factor

A.2.1 Winter Temperature

The most recent normal period (1981–2010) for Yellowknife shows an average winter (December–February) temperature of –23.5°C. Winter temperatures are a prime factor in the successful construction of winter roads, since both ground freezing and lake ice are required. Using the standard 30-year normal period, previous values of winter average temperatures can be compared as an indication of historical winter temperature trends (Figure A1). Since the earliest normal period, the average winter temperature has increased from –26°C to –23.5°C; monthly changes are greatest during January and February, with an increase of up to 3.1°C (Figure A2).

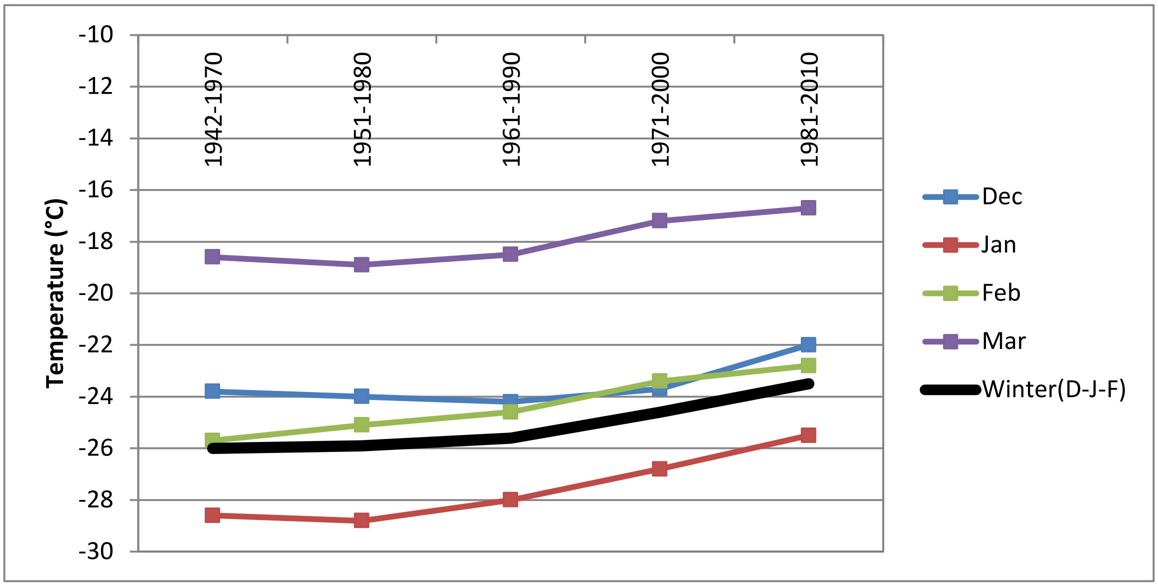


Figure A1: Historical average temperatures (°C) observed at Yellowknife A for five previous normal periods

Data source: Environment Canada 2014

The observed trend of increasingly warmer winters presents a long-term challenge to winter road operations. Although average temperatures are still very cold, increasingly warmer average winter temperatures could affect the rate of natural ice growth and the effectiveness of ice-thickening measures.

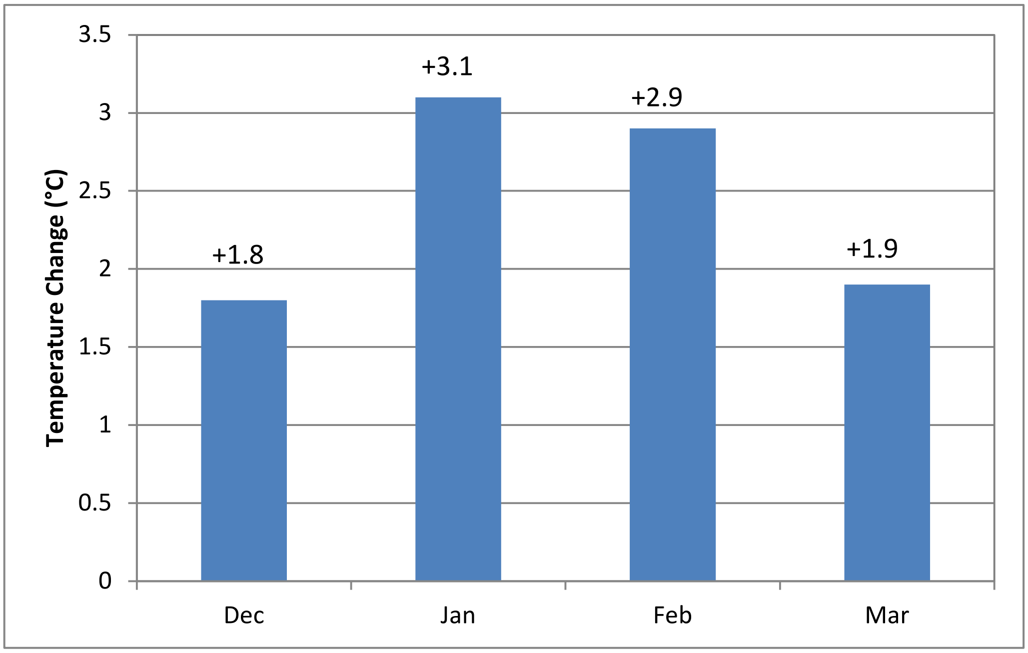


Figure A2: Change in monthly temperature normals at Yellowknife A (1942–1970 to 1981–2010)

Data source: Environment Canada 2014

Two maps of mean winter temperatures show the progression of warming temperatures between 1961 and 1990 and the most recent normal period of 1981–2010 (Figures A3 and A4). Progressively colder winter temperatures are encountered moving north in the TCWR region, with a mean most recently of –24°C in the south at Yellowknife, and the mean temperature at Contwoyto closer to –28°C. These maps are generated from the CANGRD dataset (McKenney et al. 2011). Because the winter road is primarily affected by temperature, areas along the southernmost portion of the route are more likely to be affected by warming temperatures. For this reason, a point near the centre of Gordon Lake was also selected for investigation and is discussed in section A.2.2.

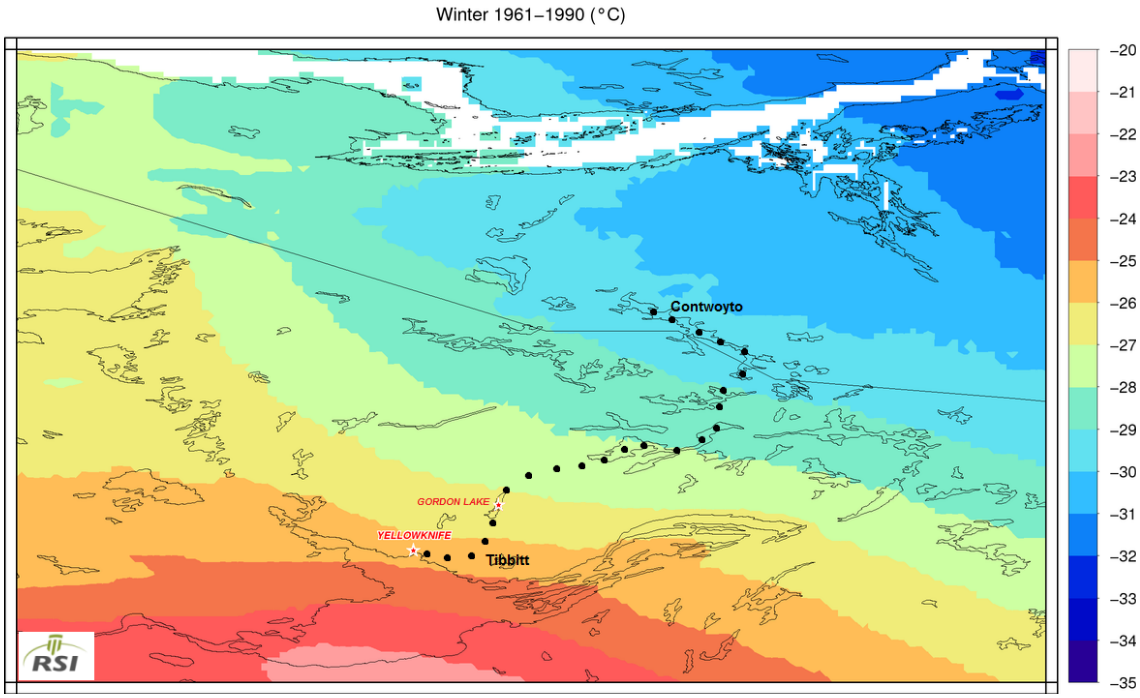


Figure A3: Mean winter (D-J-F) temperature along the TCWR, 1961–1990

Data source: McKenney et al. 2011

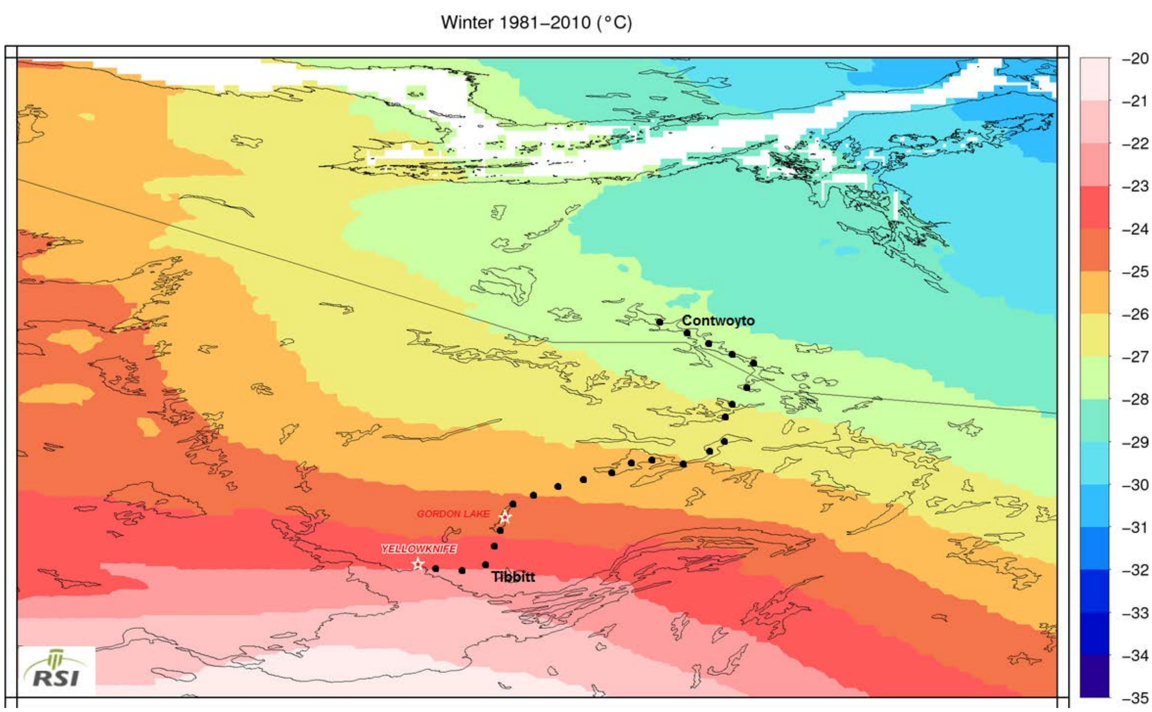


Figure A4: Mean winter (D-J-F) temperature along the TCWR, 1981–2010

Data source: McKenney et al. 2011

A.2.2 Freezing-Degree Days (FDD) and CANGRD temperature values

To provide a temperature record at Gordon Lake where none exists, the interpolated CANGRD temperature dataset was used. It involves a carefully interpolated and gridded procedure developed by McKenney et al. at 10-km resolution of daily maximum, minimum and mean temperature and precipitation (2011). To ensure its validity in this region, the time series of accumulated Freezing-Degree Days (FDD) using both datasets were calculated and compared for Yellowknife A. FDD sums the daily mean temperature values falling below 0°C, so a day with a mean temperature of –20°C would contribute 20 FDD. If the next day were –12°C, it would contribute 12 FDD, leading to an accumulation of 32 FDD for the two days. Days above 0°C contribute 0 FDD.

There was strong agreement between the observed temperatures (and therefore, FDD) between both datasets. The accumulated FDD for both datasets for the period of 1961–2010 is presented below for Yellowknife in Figure A5. FDD starts at zero on July 1 and is accumulated over the winter season to June 30 of the following year.

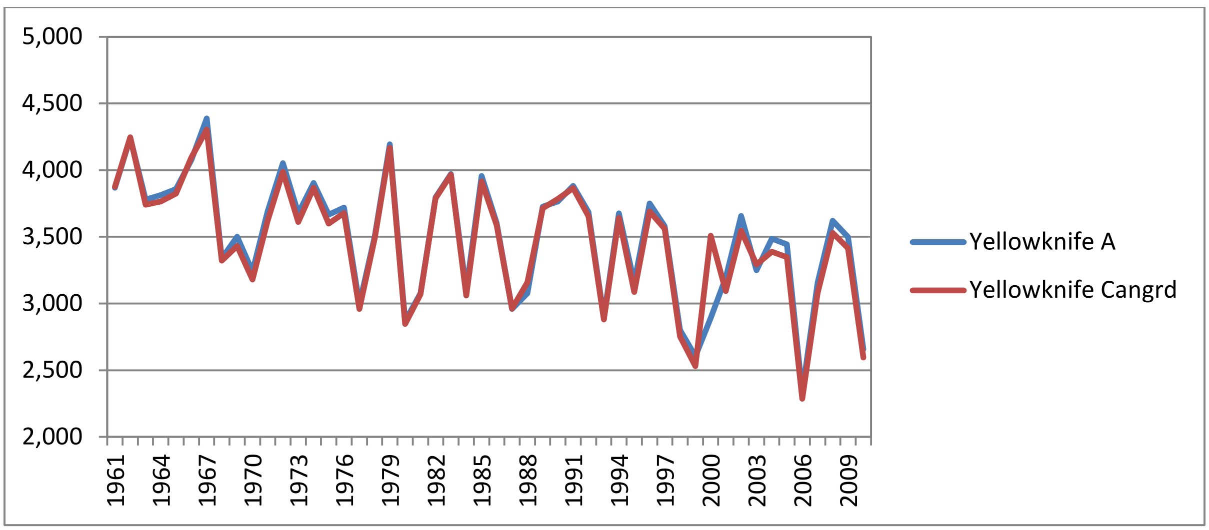


Figure A5: Accumulated FDD, Yellowknife A and Yellowknife CANGRD, 1961–2009

Data source: Environment Canada 2014; McKenney et al. 2011

Typically, FDD accumulation begins near Julian day 300 (November) and reaches its maximum near Julian day 100 (mid-April). The Environment Canada records for Yellowknife A show the profiles for the years with the highest and lowest FDD accumulation (Figure A6). The CANGRD profile would be indistinguishable from this observed profile calculated at Yellowknife A.

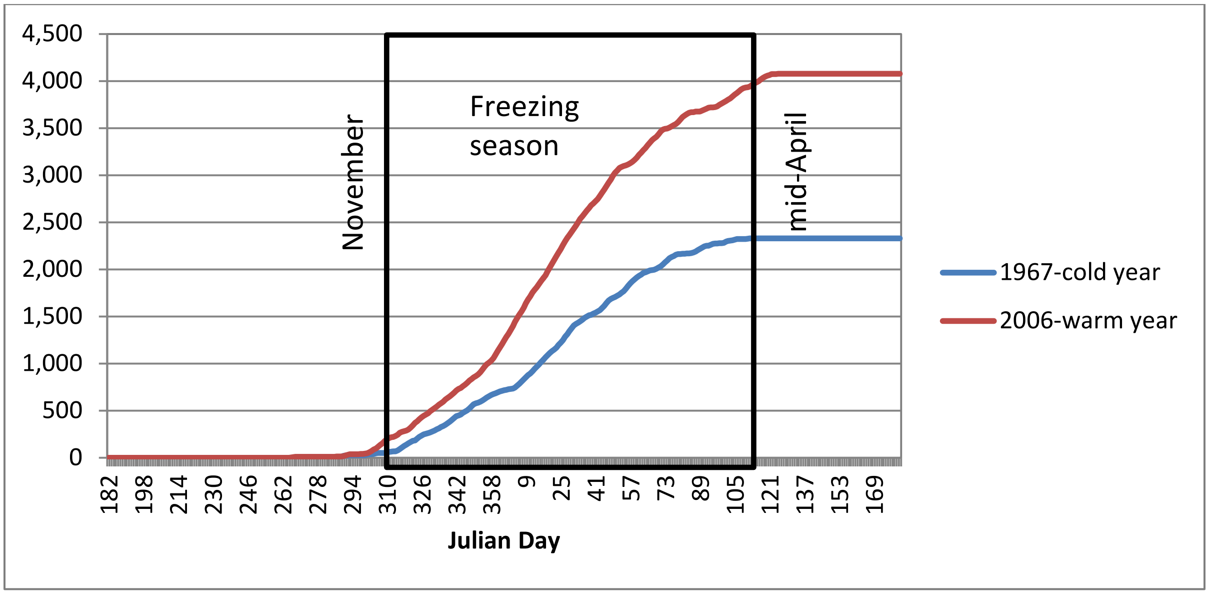


Figure A6: FDD accumulation profiles for warmest and coldest years at Yellowknife A

Data source: Environment Canada 2014

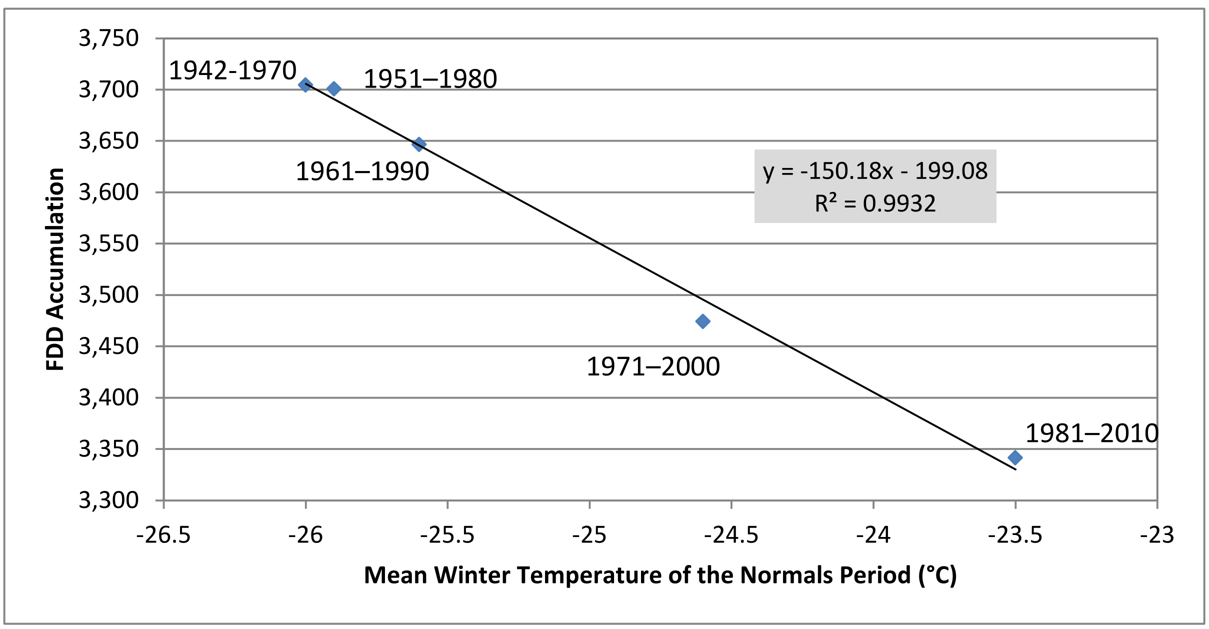


Figure A7: Correlation of FDD accumulation and mean winter temperature at Yellowknife A, 1942–2010

Data source: Environment Canada 2014

There is a high correlation between the accumulated FDD for each season and the mean winter temperature. Colder years generate higher FDD values than warmer years do. In 2006, a warm year, the FDD accumulation was close to 2,400; for the coldest year, 1967, accumulation was almost 4,000. Figure A7 shows the correlation between the average accumulated FDD for each of the previous normal periods and the mean winter temperature.

As might be expected, with the increase in mean winter temperatures, FDD accumulation has correspondingly decreased, from a value of 3,700 to approximately 3,200, as seen in Figure A8. There is high year-to-year variation: 1967 was the best year for ice formation and 2006 was the worst. The average yearly FDD accumulation (shown by the black line) is 3,521 over the period.

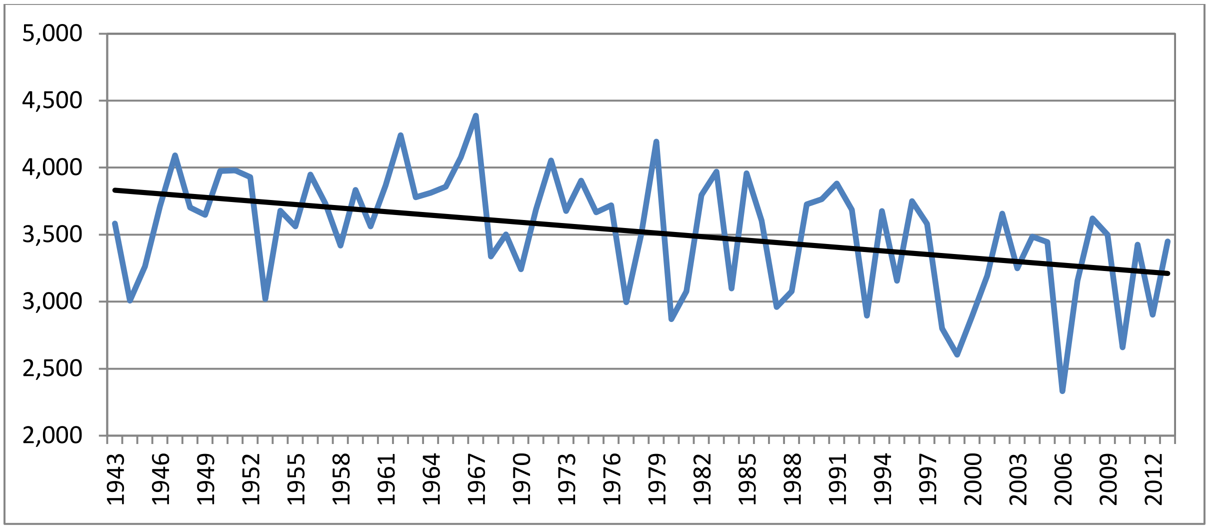


Figure A8: FDD accumulation at June 30, Yellowknife A, 1943–2013

Data source: Environment Canada 2014

To determine good versus bad years for this indicator, the mean value is used: good years (green) have higher-than-mean values and bad years (pink) have lower-than-mean values. This can be seen in Table A2 for the 1943–2013 period. There is a trend of increasingly bad years due to warming winters, which reduces the accumulated FDD for the season.

Table A2: FDD accumulation, 1943–2013

Data source: Environment Canada 2014

A.2.2.1 FDD and winter road operating period

With the data on the length of the winter road operational season since 1994 (JVMC 2013), the relationship between FDD accumulation and operational season length can be investigated. The correlation is not ideal, since other factors besides FDD affect the road season length. Some of these factors are not related to climate, such as the mining economy of that year, or whether all the materials necessary have already been transported for a particular year. Nevertheless, there is a broad association between the two variables, as seen in Figure A9, with a greater number of operating days associated with higher FDD accumulation. Simply put, colder years lead to more operating days.

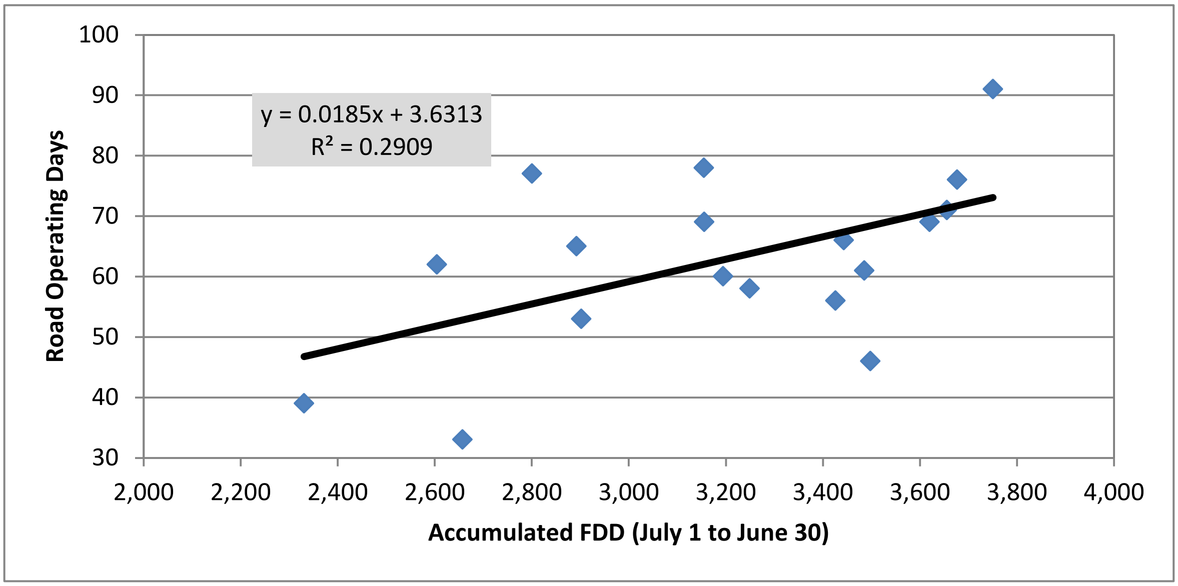


Figure A9: Comparison of TCWR operating days and FDD accumulation, 1994–2013

Data source: Environment Canada 2014; JVMC 2013

A.2.2.2 FDD and estimated ice thickness

Relationships also theoretically exist between accumulated FDD and the generation of ice (CRREL 2004). A higher accumulation of FDD increases possible ice thickness. It follows the following formula: $T = C \times FDDacc^{0.5}$ where T=ice thickness inches; C= a calibration factor related to waves, exposure, and snow; and FDDacc = accumulated Freezing-Degree Days in °F.

The C factor typically ranges between 0.2 and 0.8 during ice formation; once ice is formed this factor is ignored. These calculations used this formula with the maximum FDD accumulation at the end of the season, so C was not considered. This provided a theoretical ice thickness based on the FDD accumulation. The observations here were adjusted for use in this equation (which is based on imperial units) to produce a metric value for ice thickness. Applying the maximum yearly FDD accumulation to the equation, the resulting yearly theoretical ice thickness was calculated, ignoring all other factors (for example, snow cover or waves on lakes, which would reduce thickness). The calculation resulted in an average theoretical ice thickness of 211 cm at the beginning of the record, trending lower to an average ice thickness of 193 cm in recent years, a reduction of 18 cm (Figure A10). An accumulation of 300 FDD corresponds roughly to an ice thickness of 25 cm.

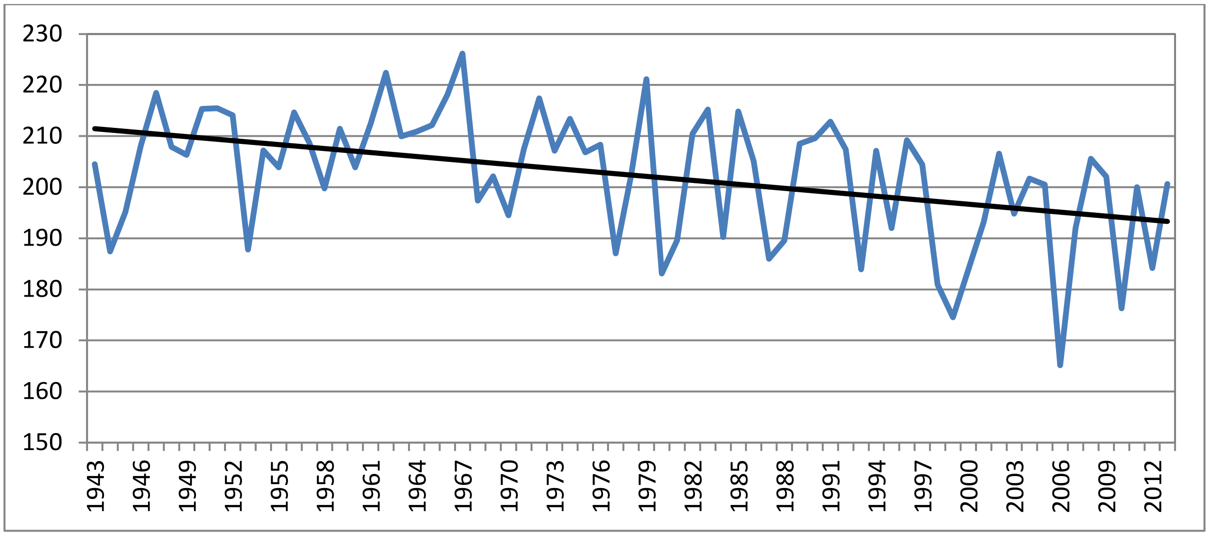


Figure A10: Estimated Ice thickness (cm) based on FDD accumulation using C coefficient at 1.0, 1943–2013

Data source: Environment Canada 2014

Environment Canada, through the Canadian Ice Service, has a record of ice thickness measurements at Yellowknife (taken nearby on Great Slave Lake) (CCIN 2013). The maximum ice thickness measurement for each season was extracted from this data and plotted in Figure A11 (there is a gap in the data between 1997 and 2004).

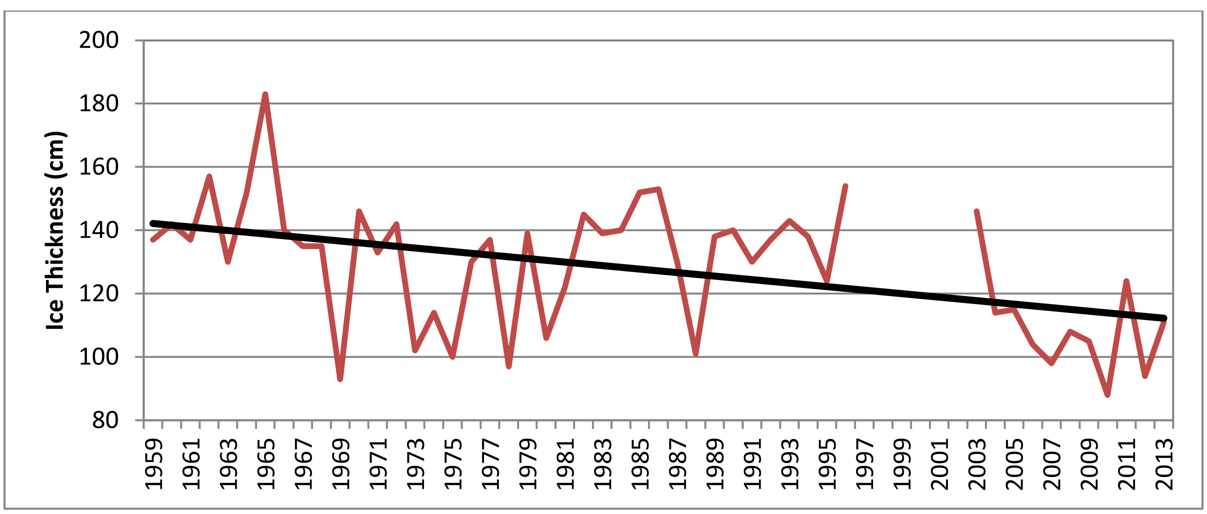


Figure A11: Observed annual maximum ice thickness, Yellowknife, 1959–2013

Data source: CCIN 2013

The observed maximum thickness is always less than the theoretical ice thickness that was calculated based on FDD accumulation. This is to be expected, since negative factors that influence ice growth are not considered in the theoretical calculation. Although the FDD-calculated ice thickness for 2006 is at a record low, this does not show up in the observed record at Yellowknife. There is an association between the two datasets (both decreasing over time), so the calculation is a meaningful indicator, although weak (Figure A12).

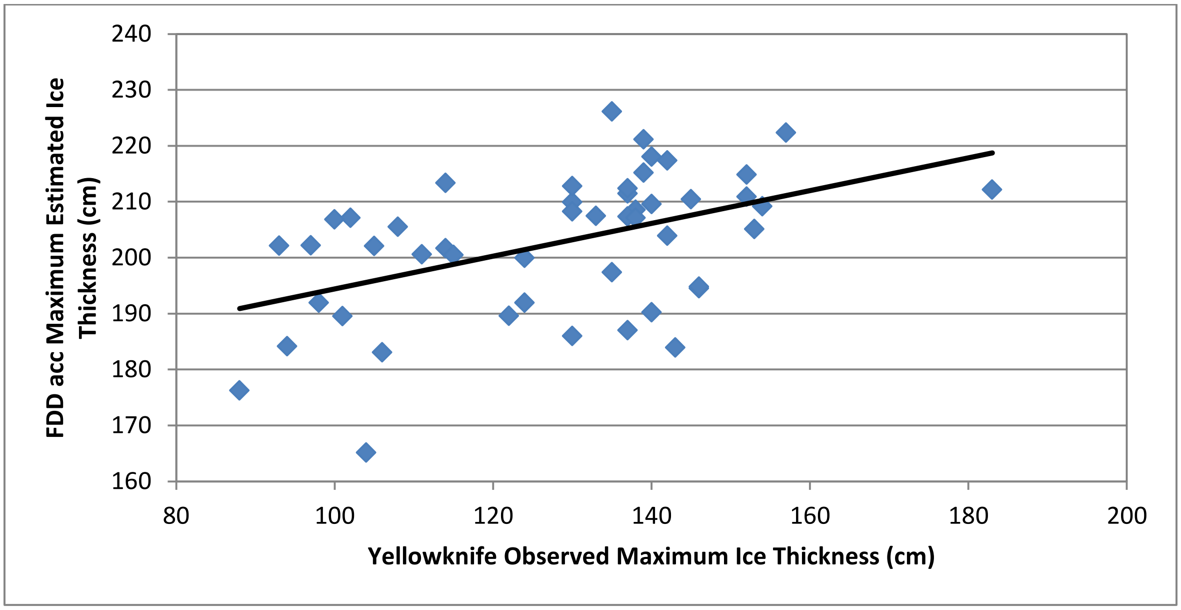


Figure A12: Comparison of observed and theoretical maximum ice thickness at Yellowknife

Data source: CCIN 2013

A.2.3 Melting-Degree Days (MDD)

This variable serves as an indicator of the potential closing of the winter road due to the accumulation of heat from days with a mean temperature greater than 0°C. MDD is the opposite of FDD. The summation starts on January 1 of each year; the value reached as of April 30 (which is beyond the winter road typical closure date) is plotted in Figure A13. The higher accumulation of MDD during the January-to-April period would be a negative influence on winter road operations because of its contribution to melting conditions.

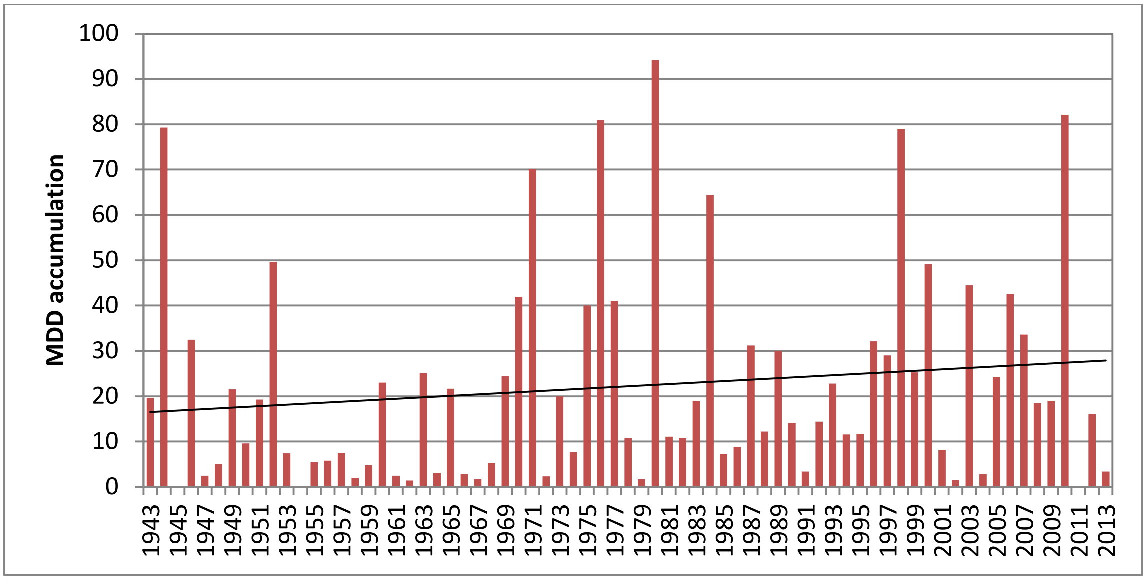


Figure A13: MDD accumulation at April 30 (Jan 1–Apr 30) at Yellowknife A, 1943–2013

Data source: Environment Canada 2014

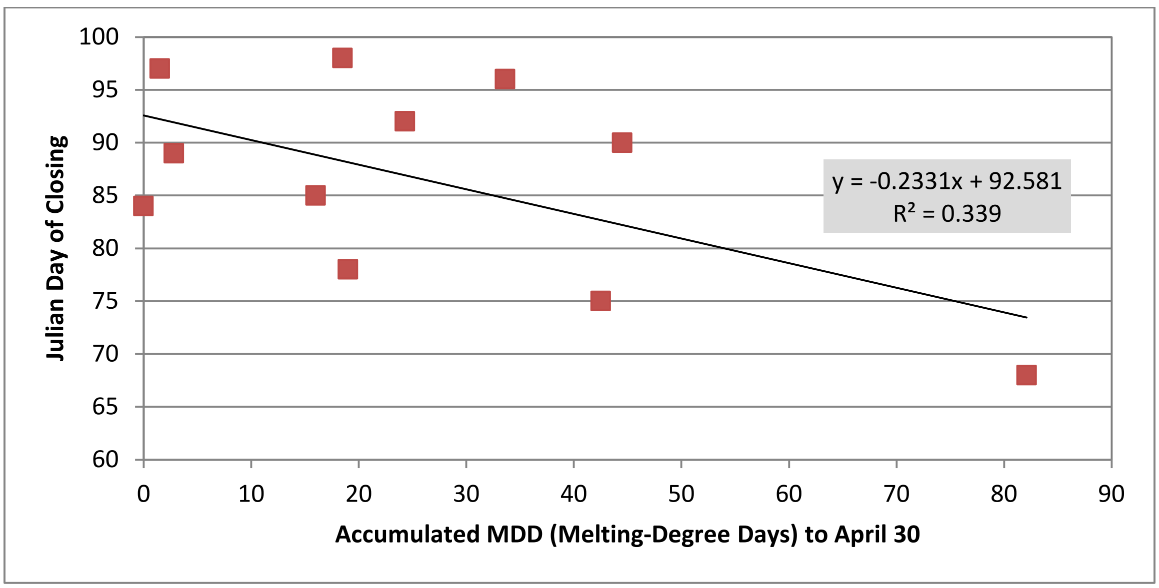


Figure A14: MDD accumulation and Julian day of road closure

Data source: Environment Canada 2014

The MDD average over the entire period was calculated (Table A3). Those years with above-average MDD are deemed bad (pink); those years with low MDD are good (green).

Table A3: Average MDD, 1943–2013

Data source: Environment Canada 2014

A.2.4 Date when Accumulated FDD reaches 300

According to Kuryk (2003), the accumulation of FDD to 306 indicates that the ice should theoretically be thick enough for winter road construction to begin. From the ice thickness formula presented in A.2.2.2, 300 FDD corresponds roughly to an ice thickness of 25 cm. This would provide enough strength to support the start of construction. Therefore, the date at which the FDD accumulation reaches 300 was determined for each year in the record. Once again, this indicator does not consider other factors that influence road construction. For this variable, the accumulated FDD used was for the previous year (i.e., the data shown for the 1971 winter road year is actually from 1970, when the ice was forming). The earlier the threshold of 300 FDD accumulation is reached, the earlier that winter road construction can begin, so colder falls and early winters lead to earlier construction starts. The dates of the 300 threshold are shown below in Figure A15. These are shown as days after November 1.

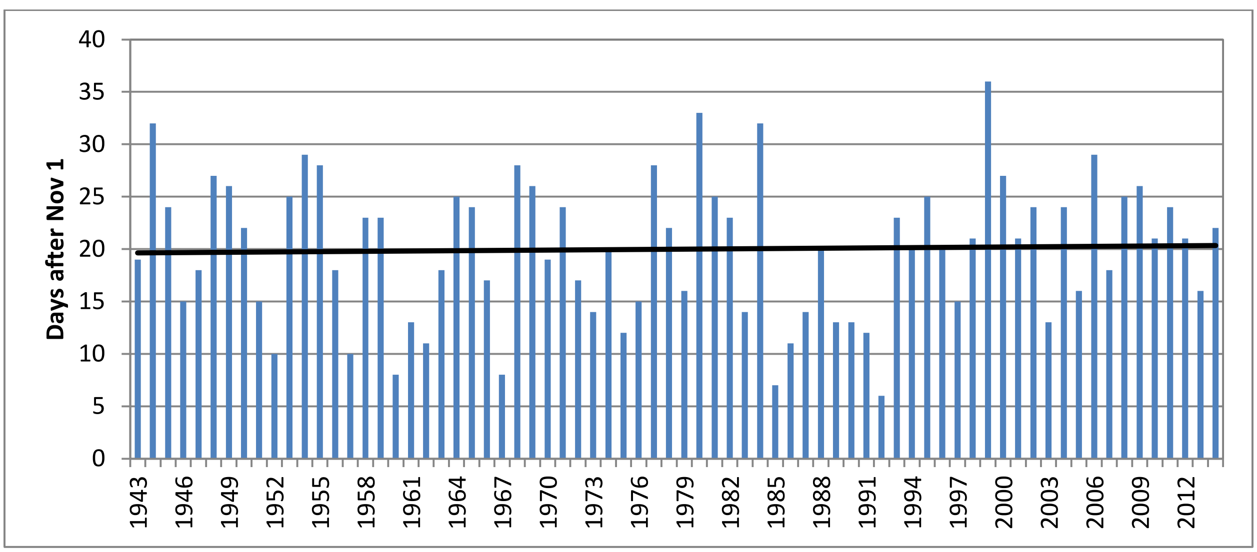


Figure A15: Days after November 1 in previous year for FDD accumulation of 300 at Yellowknife A, 1943–2013

Data source: Environment Canada 2014

Notably, there appears to be no clear trend in the date of accumulation of 300 FDD over the full period. The average date is 20 days into November. It has been as early as November 6 (1992 winter road season, so ice started forming in November 1991), and as late as December 15 (1999 winter road season, so ice started forming in December 1998).

The yearly comparison of FDD reaching 300 is summarized in Table A4. Years with above-average days (later = bad winter road years) are negative (pink) and years with below-average days (earlier = good winter road years) are green.

Table A4: FDD reaching 300, 1943–2013

Data source: Environment Canada 2014

FDD300	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013

A.2.5 Accumulated Snowfall as of January 1

This variable is obtained by summing the daily snowfall amounts recorded at Yellowknife A from the preceding year up to and including January 1 of the winter road year. This is not the same as the measured snow on ground, which can settle and melt. This variable considers only accumulated snow. As discussed earlier, snow can affect winter road development in both positive and negative ways. Higher-than-average pre-season snowfall is a negative influence on ice formation due to its insulating properties. Greater snow accumulation prevents the loss of heat from both ground and ice surfaces, thus slowing the freezing process.

Some snow is necessary, however, for the portions of the winter road that cross land. This positive effect is likely not the most important factor that contributes to ground freezing or ice formation, so for the portions of this report, this indicator considers snow to be a negative influence during the freeze-up period to January 1. The yearly trend in snowfall for Yellowknife A is presented in Figure A16.

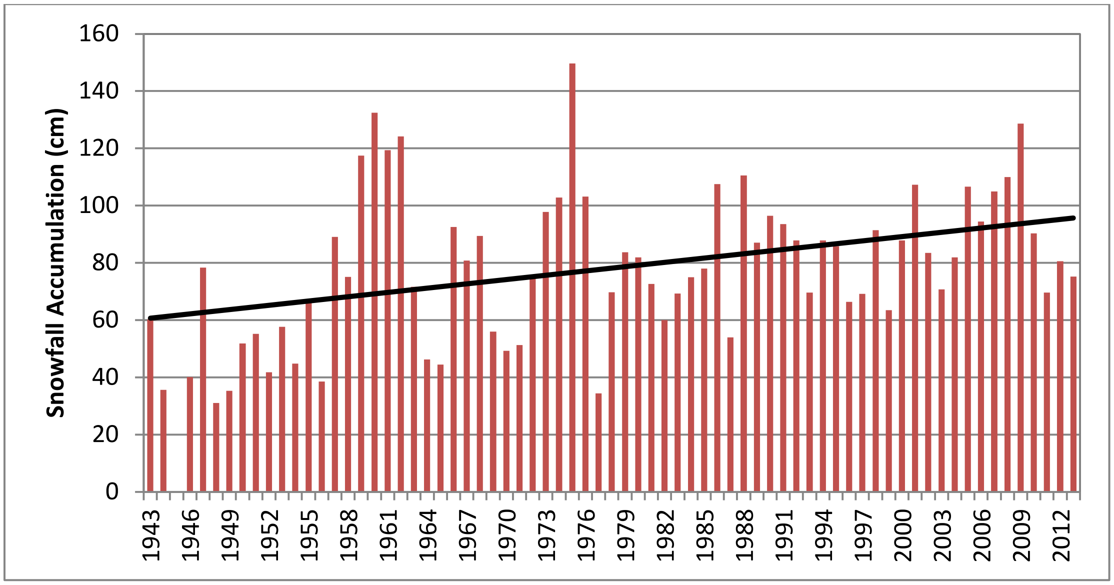


Figure A16: Snowfall accumulation at Yellowknife A to January 1, 1943–2013

Data source: Environment Canada 2014

There is a clear trend at Yellowknife of increasing snowfall. The average snowfall has increased from 60 cm to 95 cm over the entire period. Increased snowfall has also been noted for other northern Canadian locations (Vincent and Mekis 2006; L. Vincent, pers. comm.). This trend would have an increasingly negative effect on winter roads. The yearly summary of positive versus negative snowfall accumulation years is shown in Table A5, with years of less accumulation shaded green and years of more accumulation shaded pink.

Table A5: Snowfall accumulation, 1943–2013

Data source: Environment Canada 2014

A.2.6 Snow on Ground (measured) as of January 1

This variable is similar to the previous indicator (accumulated snowfall), except in this case the amount is the actual snow depth measured on the ground. It accounts for melt and settling, which the previous variable does not. This variable is not measured in as many locations or for as many years as the previous variable. As before, a larger-than-average accumulation of snow on the ground is considered a negative influence on winter road formation in the early part of the winter road season (up to January 1). The trend in snow depth on January 1 of each year is presented in Figure A17.

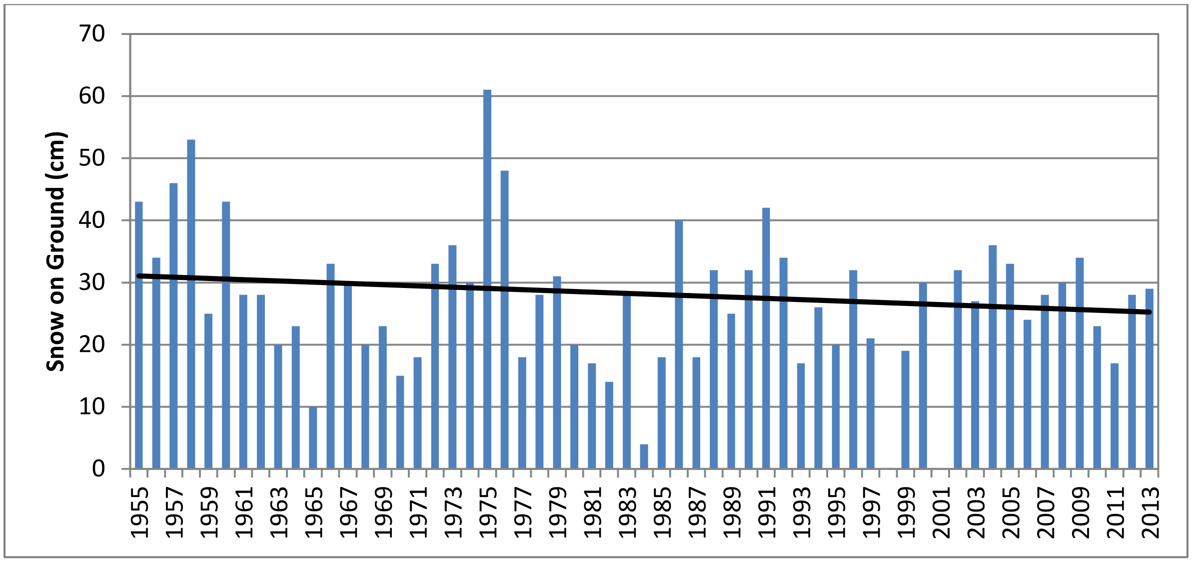


Figure A17: Snow depth measurements at Yellowknife A on January 1, 1955–2013

Data source: Environment Canada 2014

Snow depths measured at Yellowknife A have decreased slightly over time, but this trend is not significant; it represents only a very small change. The average value over the period is 28 cm. There are two missing years in this data record: 1998 and 2001 (the gaps do not indicate zero snow on ground). For this variable years with greater than the average amount of snow are negative (pink) and years with less than average snow on ground are positive (green). See Table A6.

Table A6: Snow on ground, January 1, Yellowknife, 1955–2013

Data source: Environment Canada 2014

A.2.7 Accumulated Rainfall in November and December

This indicator sums the daily rainfall values at Yellowknife A for November and December of the previous winter road year. The year shown is for the winter road year, so the value actually represents the accumulated rainfall for November and December of the previous year. Rainfall in this period signifies warm conditions and contributes negatively to the condition of the winter road through melting of the snowpack or ponding on ice. The yearly accumulation is presented in Figure A18.

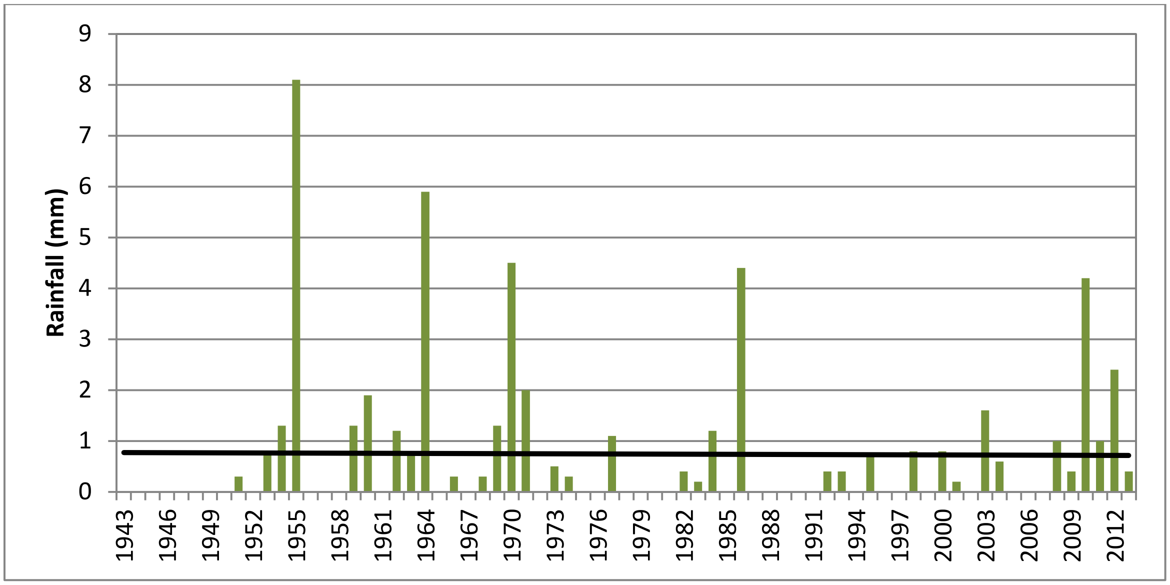


Figure A18: Accumulated rainfall in previous November and December, 1943–2013

Data source: Environment Canada 2014

For this variable, it is clear that November and December rainfall has been infrequent and likely was not of significant magnitude to affect winter roads. There is no trend of either increasing or decreasing rainfall in these months. With warming, however, rainfall could become more of a factor. November and December rainfall has occurred every year since 2008, indicating that it is becoming more frequent. Table A7 indicates above-average rainfall years in pink and below-average rainfall years in green.

Table A7: Summary of rainfall, 1943–2013

Data source: Environment Canada 2014

RainfallAc	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013

A.2.8 Days with 24-Hour Temperature Change Greater than 18°C

This indicator is calculated using the daily maximum and minimum temperatures from Yellowknife A. It counts the frequency of rapid temperature changes during the full winter road season of November to April. The year shown is the winter road year (the year in which the April falls). The change can be either an increase or a decrease; both changes could initiate cracking of the ice road surface, which would have a negative effect on operations. The yearly count of these days is presented in Figure A19.

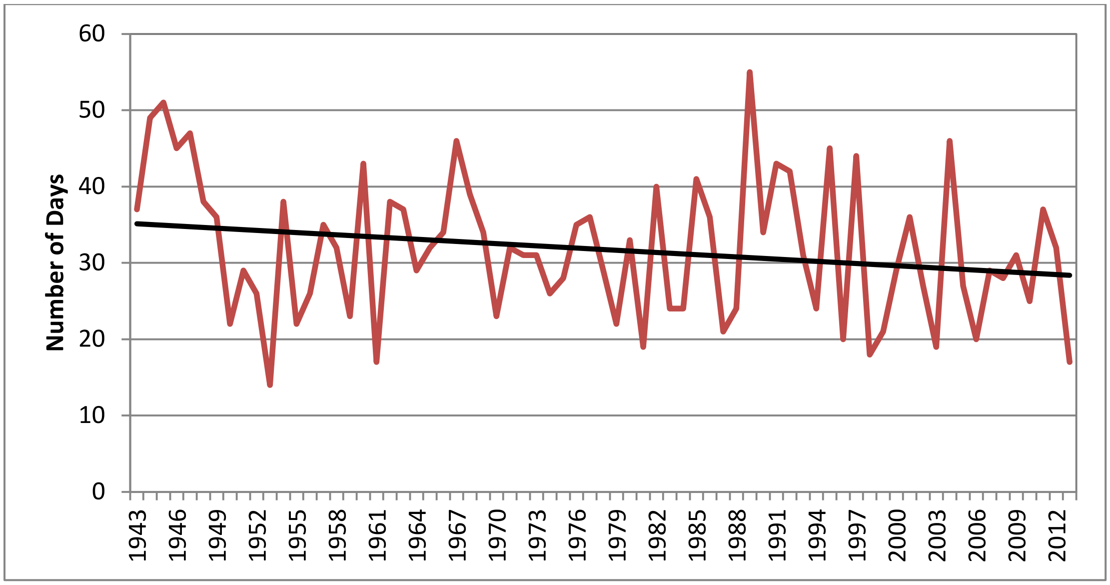


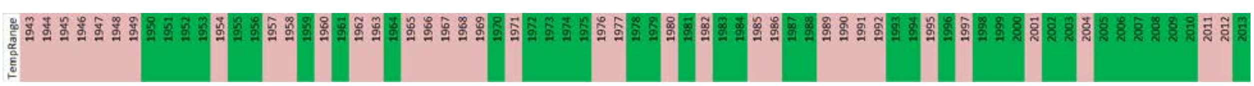
Figure A19: Number of days from November–April with temperature changes greater than 18°C, Yellowknife A, 1943–2013

Data source: Environment Canada 2014

There is a decreasing trend in days with these large temperature swings. They have decreased by about six days over the period, with an average occurrence of about 32 days each season, but the number is highly variable. The yearly index for this variable is shown in Table A8: green years have fewer-than-average large fluctuations in temperature.

Table A8: Temperature change greater than 18°C, 1943–2013

Data source: Environment Canada 2014



A.2.9 Days with Mean Temperature over Freezing

Days with a daily mean temperature above 0°C during November–April are counted for this indicator. The year indicated is the winter road year (the year in which April falls). The frequency of days above freezing would indicate melting conditions, which would be a negative factor in winter road condition. The historical occurrence of these days is presented in Figure A20.

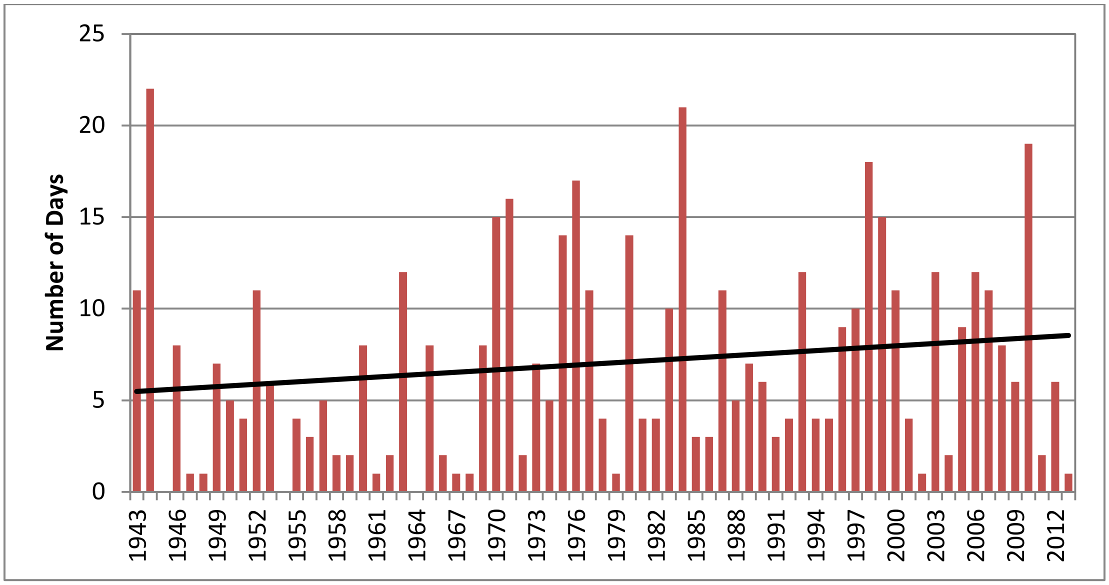


Figure A20: Days with mean temperature greater than 0°C, November–April at Yellowknife A, 1943–2013

Data source: Environment Canada 2014

Historically, the average number of days with a mean temperature greater than 0°C is seven, but there is a slight increasing trend in this indicator, suggesting a larger negative influence on winter road condition in the future. With the observed warming shown in Figures A1 and A2, this is not surprising. The year-to-year indicator for this variable is shown in Table A9.

Table A9: Mean temperature greater than 0°C, November–April, 1943–2013

Data source: Environment Canada 2014

Tmean0	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013

A.2.10 Days with 24-Hour Temperature Drop Greater than 20°C

For this indicator daily temperature maximums and minimums between November and April were compared to calculate how often the change exceeded 20°C. This indicator is important in the formation of cracks in the ice road; greater frequency is theoretically associated with more crack formation, a negative winter road factor. These frequencies are provided in Figure A21.

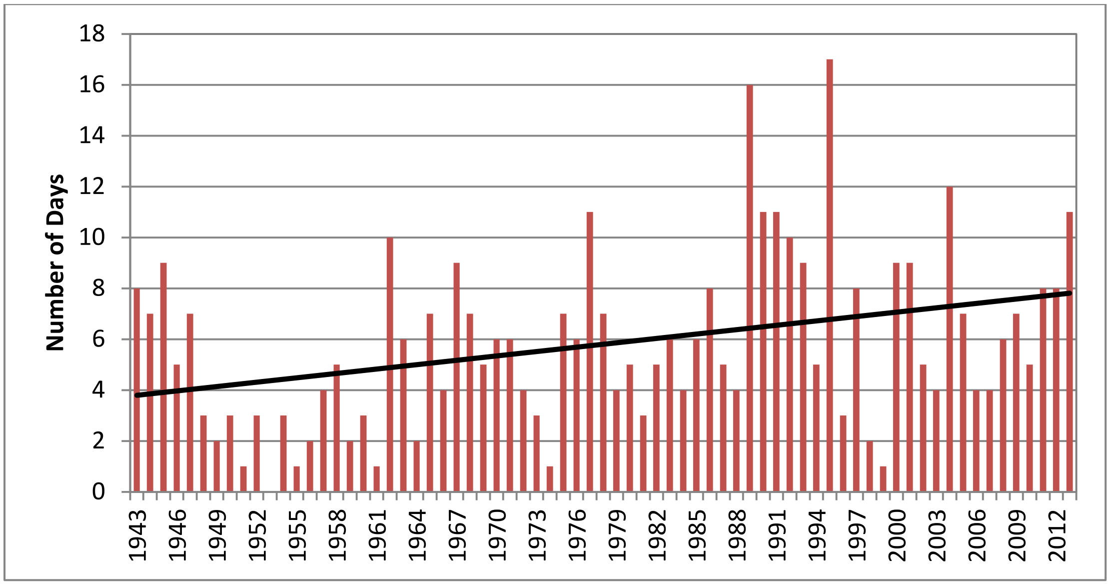


Figure A21: Days with a temperature drop greater than 20°C, November to April at Yellowknife A, 1943–2013

Data source: Environment Canada 2014

On average there have been approximately six occurrences of these drops per season, but they are increasing. It is highly unlikely that this is due to minimum temperatures becoming colder; instead, it is more likely that daily maximum temperatures are becoming warmer during the road season. Indeed, the number of days above freezing in the period (Figure A20) has also been increasing. Large drops in temperature from daytime highs to overnight lows would lead to an increase in ice cracks and formation of pressure ridges. Table A10 shows the yearly fluctuation above and below the average.

Table A10: Temperature drop greater than 20°C, 1943–2013

Data source: Environment Canada 2014

TempDrop	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013

A.2.11 Observed Lake Ice Measurements (Yellowknife, Great Slave Lake)

Figure A11, above, provides ice thickness measured by Environment Canada through the Canadian Ice Service for 1959–2013. Records were checked to obtain the maximum value measured that year. Figure A11 also shows the decreasing trend in maximum measured ice thickness. The Canadian Ice Service does not provide information on ice duration. A second dataset from the Canadian Ice Service was retrieved from the Canadian Cryospheric Information

Network (www.ccin.ca). This dataset includes information on ice duration from two locations on Great Slave Lake (Charlton Bay and McLeod Bay), the closest long-term measurement locations.

Unfortunately, the data records for these locations appear to end in 1990, predating any of the winter road operational dates, which begin in 1994. However, the length of the ice season, averaged between these two locations, also indicates that it is trending lower (by about 20 days as of 1990), as seen in Figure A22. Given the continued warming conditions since 1990, it can be safely assumed that the number of ice days has continued to decrease since then.

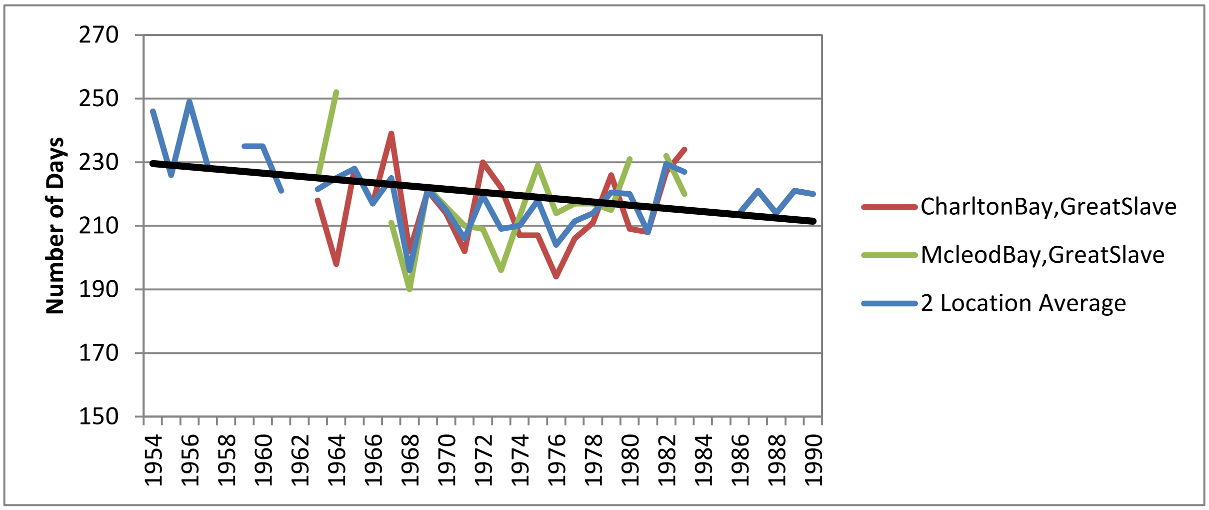


Figure A22: Ice season duration at two locations on Great Slave Lake, 1954–1990

Data source: CCIN 2013

The yearly indicator used is therefore limited to the maximum yearly ice thickness measured at Yellowknife from 1959 to 2013. During this period, the average ice maximum thickness was 128 cm. In Table A11, years with above-average ice thickness are green; those below average are pink.

Table A11: Measured maximum yearly ice thickness at Yellowknife, 1959–2013

Data source: Environment Canada 2014

YZFIceMax	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013

A.3 GORDON LAKE LOCATION

Gordon Lake is located near the southern end of the TCWR. Because there are no long-term observations from this location, the CANGRD dataset described earlier has been applied to calculate some parameters that are similar to those computed for Yellowknife A. The mean winter temperature is warmer at Yellowknife A, so it would provide the limiting case climatologically over the Gordon Lake location. This is evident from Figure A23, which compares the Yellowknife A FDD accumulation of FDD and the Gordon Lake CANGRD values. Gordon Lake, being colder and more northerly, has more freezing-degree days than Yellowknife A.

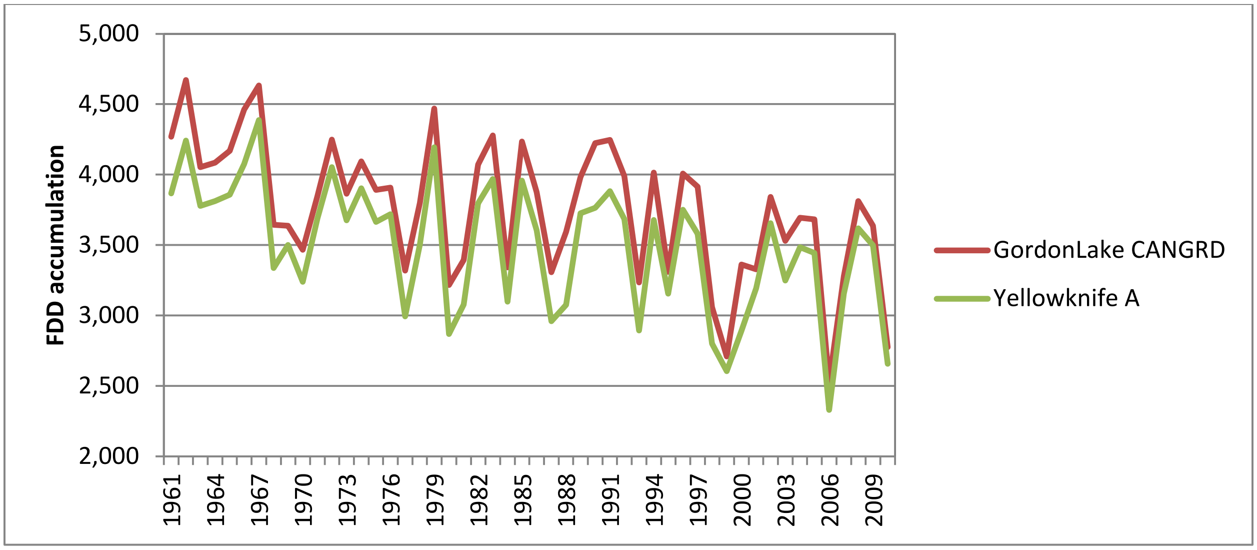


Figure A23: Comparison of FDD accumulations at June 30 at Yellowknife A and Gordon Lake, 1961–2010

Data source: Environment Canada 2014; McKenney et al. 2011

The relationship between maximum ice thicknesses predicted from these two locations can be analyzed using the formula from section A.2.2.2; see Figure A24. Gordon Lake always produces more ice than Yellowknife A does, due to its higher FDD accumulation.

Figure A25 plots the difference in yearly ice thickness between these two locations using the ice thickness formula in A.2.2.2. Larger differences in FDD accumulation produce larger differences in ice thickness. Due to differences in temperature, a location at Gordon Lake could produce more than 10 cm of ice than the thickness found at Yellowknife A. The southernmost portion of the TCWR presents the greatest limitation climatologically for winter road construction and maintenance. On the more northerly section of the road, towards Contwoyto, the colder average conditions favour winter road operation.

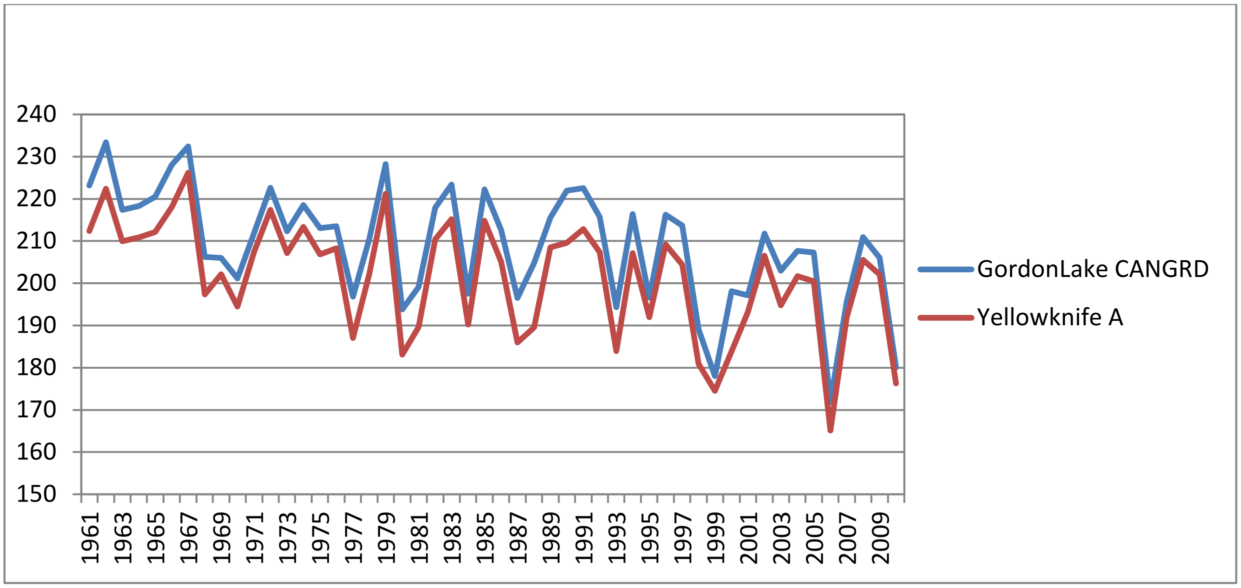


Figure A24: Estimated maximum ice thickness calculated from FDD accumulation at Yellowknife A and Gordon Lake, 1961–2010

Data source: Environment Canada 2014; McKenney et al. 2011

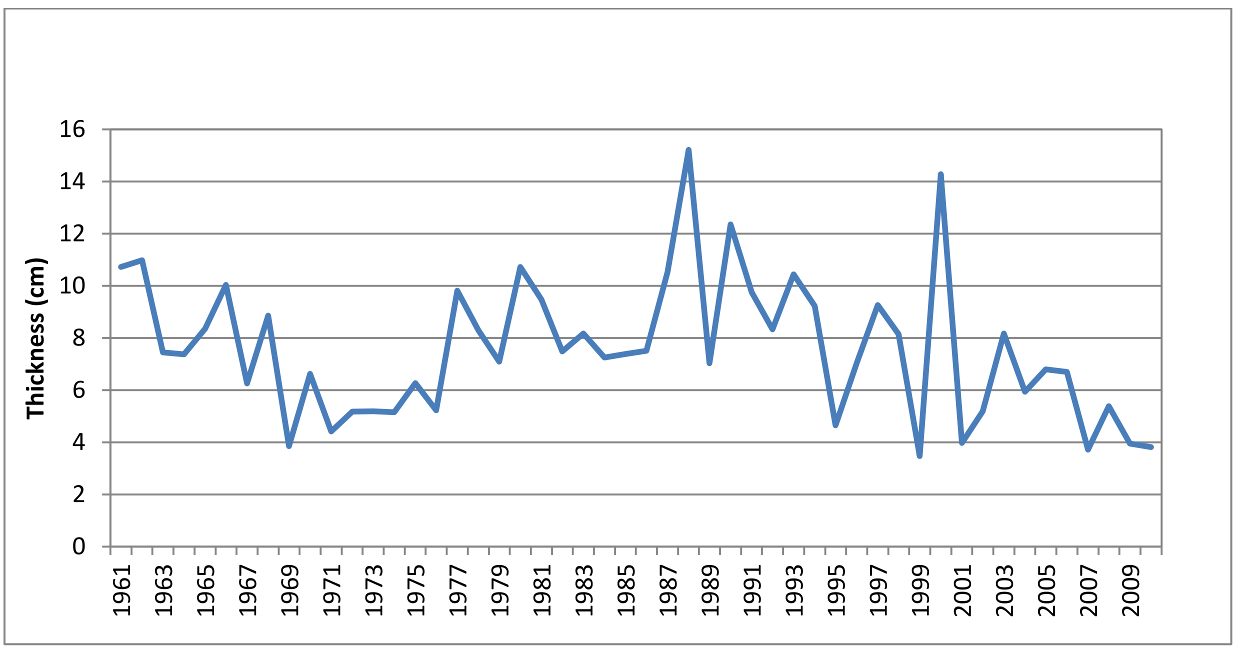


Figure A25: Estimated difference in maximum ice thickness between Yellowknife A and Gordon Lake, 1961–2010

Data source: Environment Canada 2014; McKenney et al. 2011

A.4 SUMMARY OF CLIMATE FACTORS INFLUENCING THE TCWR

Ten factors were calculated for the TCWR (Table A12) using data from Yellowknife A, the closest long-term monitoring station available.

Table A12: Ten climate factors influencing the TCWR

1	Accumulated Freezing-Degree Days (FDDAcc)	Higher accumulation – positive factor
2	Date (Nov 1 = 1) of Accumulated FDD at 300 threshold (FDD300)	Earlier date – positive factor
3	Accumulated Melting-Degree Days (MDDAcc)	Higher accumulation – negative factor
4	Accumulated snowfall at January 1 (the sum of observed daily snowfall) (SnowAcc)	Higher accumulation – negative for ice portion of road, but necessary for the land portion of the road. Since ice formation is critical, this is considered here as a predominantly negative factor
5	Snow on ground at January 1 (measured snow on ground) (SnowGrnd)	As above – predominantly a negative factor
6	Accumulated rainfall in November and December prior to the winter road season (RainAcc)	Higher accumulation – negative factor, since it contributes to melting ice/snow
7	Days with 24-hour temperature change greater than 18°C in November to April (TempRange)	Higher value – negative factor, since contributes to ice road crack formation
8	Days with mean temperature above 0°C in November to April (TempMean)	Higher value – negative factor, since it contributes to melting ice/snow
9	Days with 24-hour temperature drop greater than 20°C in November to April (TempDrop)	Higher value – negative factor since it contributes to the formation of ice road cracks
10	Observed ice thickness (Yellowknife, Great Slave Lake) (IceThck)	Higher value – positive factor

An investigation of the differences between Yellowknife A and a location at Gordon Lake show, not surprisingly, that limiting conditions are more likely to occur on the south portion of the road. The Yellowknife A indicators were compared against one another in Table A13 to identify good versus bad winter road years. These are determined by operating season length, data for which is provided by the JVMC and inferred from a chart in Hayley and Proskin 2008. Combining these two sets of data, season lengths are available from 1994 to 2013.

The average value of each factor over the period of each data record was determined: positive winter road years (above average) are green and negative winter road years are pink (Table A13). Colour coding enables quick determination of factors that contribute to longer operating seasons (green), or shorter operating seasons (pink).

Table A13: Value of climate factors (blank cells represent data gaps)

Data source: Environment Canada 2014; McKenney et al. 2011; JVMC 2013

Year	FDD Acc	FDD 300	MDD Acc	Snow Acc	Snow Grnd	Rain Acc	Temp Range	Temp Mean	Temp Drop	Ice Thck	OP Days
1943	3,583	19	19.6	60.2		0	37	11	8		
1944	3,008	32	79.3	35.6		0	49	22	7		
1945	3,263	24	0			0	51	0	9		
1946	3,712	15	32.5	40.1		0	45	8	5		
1947	4,092	18	2.5	78.3		0	47	1	7		
1948	3,703	27	5.1	31.1		0	38	1	3		
1949	3,648	26	21.5	35.3		0	36	7	2		
1950	3,974	22	9.6	51.9		0	22	5	3		
1951	3,979	15	19.3	55.2		0.3	29	4	1		
1952	3,929	10	49.6	41.8		0	26	11	3		
1953	3,019	25	7.4	57.7		0.8	14	6	0		
1954	3,679	29	0	44.8		1.3	38	0	3		
1955	3,562	28	5.4	66.1	43	8.1	22	4	1		
1956	3,949	18	5.8	38.6	34	0	26	3	2		
1957	3,731	10	7.5	89.1	46	0	35	5	4		
1958	3,417	23	2	75.1	53	0	32	2	5		
1959	3,833	23	4.8	117.5	25	1.3	23	2	2	137	
1960	3,563	8	23	132.4	43	1.9	43	8	3	142	
1961	3,868	13	2.5	119.4	28	0	17	1	1	137	
1962	4,241	11	1.4	124.2	28	1.2	38	2	10	157	
1963	3,778	18	25.1	71.6	20	0.8	37	12	6	130	
1964	3,812	25	3.1	46.3	23	5.9	29	0	2	152	
1965	3,858	24	21.7	44.5	10	0	32	8	7	183	
1966	4,077	17	2.8	92.5	33	0.3	34	2	4	140	
1967	4,387	8	1.7	80.8	30	0	46	1	9	135	

Year	FDD Acc	FDD 300	MDD Acc	Snow Acc	Snow Grnd	Rain Acc	Temp Range	Temp Mean	Temp Drop	Ice Thck	OP Days
1968	3,337	28	5.3	89.4	20	0.3	39	1	7	135	
1969	3,501	26	24.4	56	23	1.3	34	8	5	93	
1970	3,240	19	41.9	49.3	15	4.5	23	15	6	146	
1971	3,689	24	70.1	51.3	18	2	32	16	6	133	
1972	4,052	17	2.3	74.9	33	0	31	2	4	142	
1973	3,676	14	20	97.8	36	0.5	31	7	3	102	
1974	3,903	20	7.7	102.8	30	0.3	26	5	1	114	
1975	3,666	12	40	149.7	61	0	28	14	7	100	
1976	3,719	15	80.9	103.2	48	0	35	17	6	130	
1977	2,995	28	41	34.4	18	1.1	36	11	11	137	
1978	3,504	22	10.7	69.7	28	0	29	4	7	97	
1979	4,195	16	1.7	83.7	31	0	22	1	4	139	
1980	2,869	33	94.2	81.9	20	0	33	14	5	106	
1981	3,078	25	11.1	72.6	17	0	19	4	3	122	
1982	3,796	23	10.7	60	14	0.4	40	4	5	145	
1983	3,970	14	19	69.3	28	0.2	24	10	6	139	
1984	3,099	32	64.4	75	4	1.2	24	21	4	140	
1985	3,957	7	7.3	78	18	0	41	3	6	152	
1986	3,605	11	8.8	107.5	40	4.4	36	3	8	153	
1987	2,961	14	31.2	54	18	0	21	11	5	130	
1988	3,077	20	12.2	110.5	32	0	24	5	4	101	
1989	3,727	13	30	87.1	25	0	55	7	16	138	
1990	3,765	13	14.1	96.5	32	0	34	6	11	140	
1991	3,882	12	3.4	93.5	42	0	43	3	11	130	
1992	3,685	6	14.4	87.8	34	0.4	42	4	10	137	
1993	2,895	23	22.8	69.6	17	0.4	31	12	9	143	
1994	3,677	20	11.6	87.8	26	0	24	4	5	138	76
1995	3,155	25	11.7	85.8	20	0.7	45	4	17	124	78
1996	3,751	20	32.1	66.4	32	0	20	9	3	154	91*
1997	3,581	15	29	69.2	21	0	44	10	8		
1998	2,801	21	79	91.4		0.8	18	18	2		77
1999	2,605	36	25.3	63.5	19	0	21	15	1		62
2000	2,892	27	49.1	87.8	30	0.8	29	11	9		65
2001	3,195	21	8.2	107.3		0.2	36	4	9		60
2002	3,656	24	1.5	83.5	32	0	27	1	5		71
2003	3,250	13	44.5	70.8	27	1.6	19	12	4	146	58
2004	3,486	24	2.8	81.9	36	0.6	46	2	12	114	61
2005	3,444	16	24.3	106.6	33	0	27	9	7	115	66

Year	FDD Acc	FDD 300	MDD Acc	Snow Acc	Snow Grnd	Rain Acc	Temp Range	Temp Mean	Temp Drop	Ice Thck	OP Days
2006	2,331	29	42.5	94.4	24	0	20	12	4	104	39
2007	3,156	18	33.6	105	28	0	29	11	4	98	69
2008	3,620	25	18.5	110	30	1	28	8	6	108	69
2009	3,498	26	19	128.7	34	0.4	31	6	7	105	46
2010	2,658	21	82.1	90.3	23	4.2	25	19	5	88	33*
2011	3,426	24	0	69.6	17	1	37	2	8	124	56
2012	2,903	21	16	80.6	28	2.4	32	6	8	94	53
2013	3,448	16	3.4	75.2	29	0.4	17	1	11	111	
AVG	**3,522**	**20**	**22**	**78**	**28**	**0.7**	**32**	**7**	**6**	**128**	**63**

As shown in the last column, OP days (operating season length), the longer-than-average seasons are most strongly associated with FDDAcc, since that variable correctly assigns five of the nine good years and all nine of the lower-than-average years. This demonstrates the high degree of thermal control compared to other factors in this location (such as snow and rain).

The high and low years in terms of operating season length — 1996 and 2010 — are marked with an asterisk. The high year is 1996 which also has the highest FDDAcc for years which there is data on operating season length. FDDAcc is highest for years with long operating seasons. In 1996 there was also lower than average snowfall, no rain, fewer than average temperature fluctuations and temperature drops and higher-than-average ice thickness measured at Yellowknife.

For 2010, which had the fewest number of operating days, there were only three positive factors: the snow on ground was less than average, and the number of daily temperature ranges and temperature drops was also less than average. A more important negative factor was the FDDAcc that year, which was among the lowest recently recorded. The lowest FDDAcc occurred in 2006, which also had a very short operating season.

Further inferences can be made from these indicators for specific years and the relationships could be better defined with data for more years of operating season length. Clearly, some variables appear to not be very useful, such as TempRange, which indicates too many good years.

Another complication in evaluating operating season length was alluded to earlier: the length could be determined by entirely non-climatological factors such as economic strength of the mines or simply completing all the required transports for the season early.

A. 5 CONCLUSIONS AND FURTHER WORK

A comprehensive investigation of climatological factors influencing winter road construction and operation for the TCWR was undertaken. It used available data, primarily from the closest long-term observation station at Yellowknife A. Yearly indices of importance to the road were calculated and compared against years with available information about length of the operating season. The strongest indicator for longer versus shorter seasons is the accumulation of freezing-degree days. Other factors considered, such as large daily temperature fluctuations, appear to have no significant impact on season length. The relationship between the yearly climatological indices and season length could likely be refined with more years of operational information. Nevertheless, this tabular evaluation of good versus bad years in relation to average conditions provides a useful test of the veracity of the indicators and suggests which should be considered more closely.

Further work could consider the projections of climate change from the AR5 model projections from the Intergovernmental Panel on Climate Change (IPCC 2013). Projections of temperature and precipitation change from the current baseline period could then be used to recalculate these indices for the future and assess their implication for length of the winter road season. From the existing trends in temperature, it is obvious that greater challenges lie ahead under climate change. These challenges must be addressed by informed adaptation techniques, including the use of enhanced technology and building techniques that are already underway on the TCWR. These advances will become more and more important in the future, based on historical trends and climate change projections.

APPENDIX B: FUTURE CLIMATE ANALYSIS

Tibbitt to Contwoyto Mining Road

Future Climate Analysis

Prepared for:
Northern Climate ExChange (NCE)
Yukon Research Centre, Yukon College

April 25, 2014

B.1 INTRODUCTION

The Tibbitt to Contwoyto Winter Road is a 400- to 600-km private winter road that services mining locations to the northeast of Yellowknife. It has been in seasonal service since 1982. It consists of both lake crossings (87% of length) and portages, both of which are intricately related to yearly climate. The travel season is primarily during the months of February and March, averaging 67 days (JVMC 2013), although weather affects road construction and operations significantly from year to year. Appendix A investigated some of the historical climate indicators that have affected road construction and operation. Appendix B projects some future changes, based on the recent AR5 model projections from the Intergovernmental Panel on Climate Change (IPCC 2013).

B.2 PROJECTION DATA

The models used in the AR5 assessment are from the Fifth Coupled Model Intercomparison Project (CMIP5), coordinated by the World Climate Research Program (Taylor, Stouffer and Meehl 2012).

Since the second IPCC Assessment (IPCC 1995), the number of contributing international climate modelling centres and models — and their complexity — have increased significantly, from 11 models to the current 40. With increased computing power, better refinement of atmospheric phenomena has been incorporated, and spatial and temporal resolution has improved (Kharin et al. 2013). An important outcome of this is the ability to produce projections of future climate based on an ensemble of many models.

In Appendix B, all available AR5 model runs (many models have more than a single projection available) were used. The use of multiple models to generate a best estimate of climate change is preferred over a single-model outcome. Research has indicated that the use of multi-model ensembles is preferable, since each model can contain inherent biases and weaknesses (IPCC-TGICA 2007; Tebaldi and Knutti 2007). The use of an ensemble projection is likely the most reliable estimate of climate change projections on a large scale (Gleckler, Taylor and Doutriaux 2008).

A list of the climate models and their country of origin is presented in Table B1.

Table B1: List of climate models and their country of origin (Taylor, Stouffer and Meehl 2012)

Model Name	Organization	Country	Organization Details
ACCESS1-0	CSIRO-BOM	Australia	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)
ACCESS1-3	CSIRO-BOM	Australia	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)
BCC-CSM1-1	BCC	China	Beijing Climate Center, China Meteorological Administration
BCC-CSM1-1-M	BCC	China	Beijing Climate Center, China Meteorological Administration
BNU-ESM	GCESS	China	College of Global Change and Earth System Science, Beijing Normal University
CanESM2	CCCma	Canada	Canadian Centre for Climate Modelling and Analysis
CCSM4	NCAR	US	National Center for Atmospheric Research
CESM1BGC	NSF-DOE-NCAR	US	National Science Foundation, Department of Energy, National Center for Atmospheric Research
CESM1-CAM	NSF-DOE-NCAR	US	National Science Foundation, Department of Energy, National Center for Atmospheric Research
CMCC-CESM	CMCC	Italy	*Centro Euro-Mediterraneo per I Cambiamenti Climatici*
CMCC-CM	CMCC	Italy	*Centro Euro-Mediterraneo per I Cambiamenti Climatici*
CMCC-CMS	CMCC	Italy	*Centro Euro-Mediterraneo per I Cambiamenti Climatici*
CNRM-CM5	CNRM-CERFACS	France	*Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique*
CSIRO-Mk3-6-0	CSIRO-QCCCE	Australia	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence
FGOALS-g2	LASG-IAP	China	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences
FGOALS-s2	LASG-IAP	China	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences

Model Name	Organization	Country	Organization Details
FIO-ESM	FIO	China	The First Institute of Oceanography, SOA
GFDL-CM3	NOAA GFDL	US	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2G	NOAA GFDL	US	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	NOAA GFDL	US	Geophysical Fluid Dynamics Laboratory
GISS-E2-H	NASA GISS	US	NASA Goddard Institute for Space Studies
GISS-E2-H-CC	NASA GISS	US	NASA Goddard Institute for Space Studies
GISS-E2-R	NASA GISS	US	NASA Goddard Institute for Space Studies
GISS-E2-R-CC	NASA GISS	US	NASA Goddard Institute for Space Studies
HadCM3	MOHC	UK	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by *Instituto Nacional de Pesquisas Espaciais/*INPE)
HadGEM2-AO	MOHC	UK	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by INPE)
HadGEM2-CC	MOHC	UK	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by INPE)
HadGEM2-ES	MOHC	UK	MetOffice Hadley Centre (additional HadGEM2-ES realizations contributed by INPE)
INMCM4	INM	Russia	Institute for Numerical Mathematics
IPSL-CM5A-LR	IPSL	France	*Institut Pierre-Simon Laplace*
IPSL-CM5A-MR	IPSL	France	*Institut Pierre-Simon Laplace*
IPSL-CM5B-LR	IPSL	France	*Institut Pierre-Simon Laplace*
MIROC-ESM	MIROC	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC-ESM-CHEM	MIROC	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies

Model Name	Organization	Country	Organization Details
MIROC4h	MIROC	Japan	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MIROC5	MIROC	Japan	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MPI-ESM-LR	MPI-M	Germany	Max Planck Institute for Meteorology
MPI-ESM-MR	MPI-M	Germany	Max Planck Institute for Meteorology
MRI-CGCM3	MRI	Japan	Meteorological Research Institute
NorESM1-M	NCC	Norway	Norwegian Climate Centre
NorESM1-ME	NCC	Norway	Norwegian Climate Centre

A new initiative in the IPCC AR5 is the use of Representative Concentration Pathways (RCPs). They represent a range of possible projection outcomes based on various degrees of atmospheric warming. Factors that influence RCPs include population growth, economic growth, degree of urbanization, land-use change, use of green versus carbon-based energy sources and any future international agreements on GHG emissions.

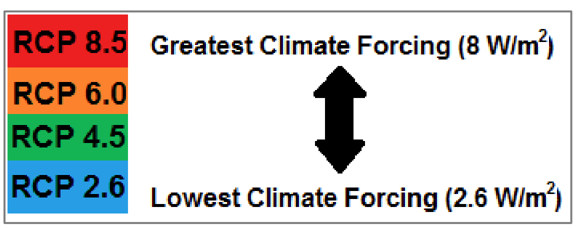


Figure B1: Estimates of climate forcing (influences on climate that originate outside the climate system)

Source: IPCC 2013

The lowest RCP (2.6) represents an increase of 2.6 watts per square metre (W/m^2) to the climate system; the highest RCP (8.5) represents an increase of 8.5 W/m^2 (Figure B1). This range encompasses the best estimate of what is possible under a small increase in warming (2.6) and a large increase in warming (8.5).

It is unknown which RCP will apply in the future. However, it is important to note that historically, greenhouse gas (GHG) emissions have followed the highest RCP (8.5). In the absence of a global agreement on GHG reduction, this trend is expected to continue, which would support this pathway going forward (Peters et al. 2012). Figure B2 shows both 4.5 (moderate) and 8.5 (high) projected changes. The number of models used for the ensemble varies with the RCP selected, since not all international modelling centres generated model runs for all RCPs. On average, approximately 75 model runs contribute to each RCP ensemble average.

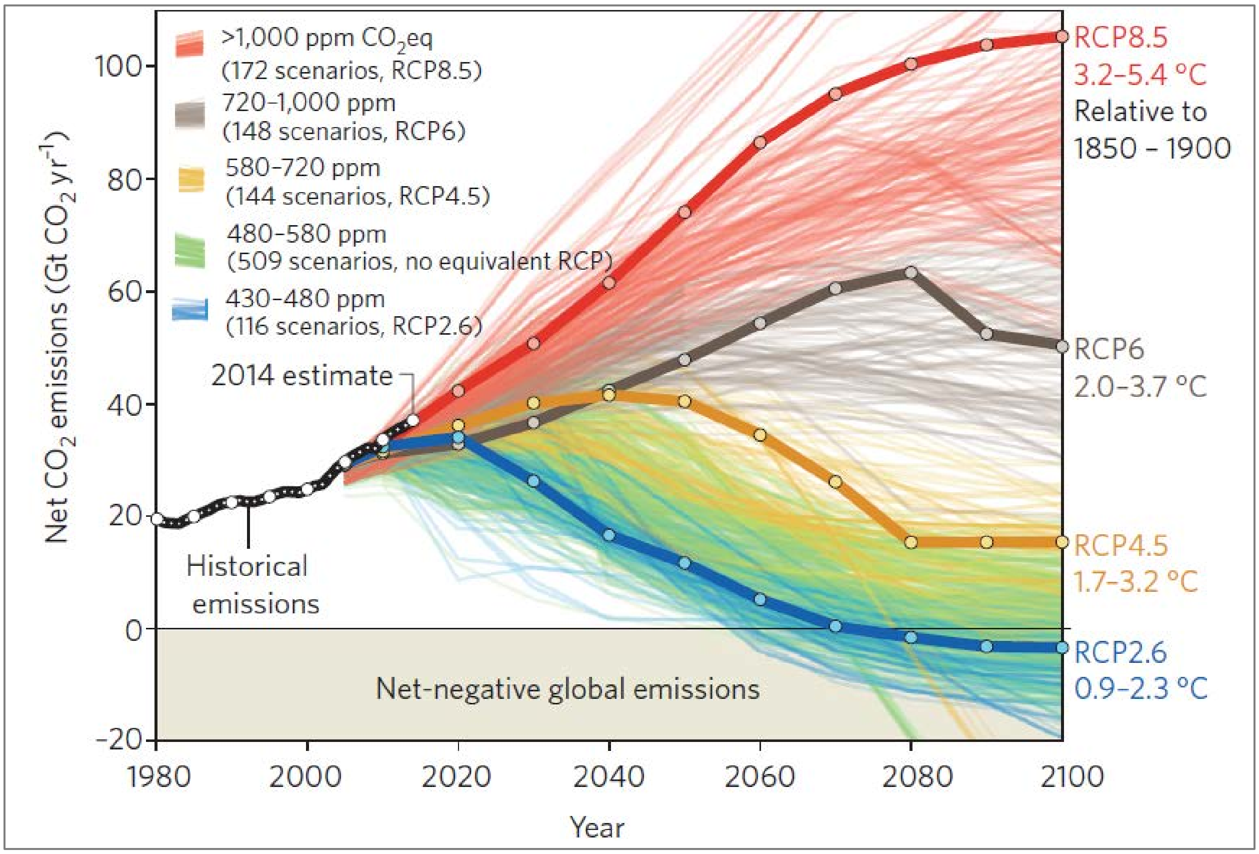


Figure B2: Global CO_2 emissions and their relationship to RCPs

Source: Fuss et al. 2014

The report of IPCC AR5 Working Group 1 provides general details of the IPCC position on climate change (IPCC 2013). Some of the main findings of this report are summarized in the *Summary for Policymakers* (IPCC 2014) and are reproduced below:

- Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades or millennia. The atmosphere and ocean have warmed, amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

- Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (the beginning of temperature records).
- Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink in most places in the world, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease.
- Atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years.
- Human influence on the climate system is clear. This is evident from the increasing GHG concentrations in the atmosphere, positive radiative forcing (i.e., increasing energy in the atmosphere), observed warming, and better understanding of the climate system.
- Human influence has been detected in the warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. This evidence of human influence has grown since AR4. It is extremely likely (>95% probability) that human influence has been the dominant cause of observed warming since the mid-20th century.
- Observational and model studies of temperature change, climate feedbacks and changes in the Earth's energy budget provide confidence in the magnitude of global warming in response to past and future forcing.
- Climate models have improved since the IPCC's Fourth Assessment Report (IPCC 2007). Models now reproduce observed continental-scale patterns and trends in surface temperature over many decades, including more rapid warming since the mid-20th century and the cooling that immediately follows large volcanic eruptions.
- The change in global surface temperature by the end of the 21st century is likely to exceed 1.5°C relative to 1850–1900 for all RCP scenarios except RCP2.6. It is likely to exceed 2°C for RCP6.0 and RCP8.5, and more likely than not to exceed 2°C for RCP4.5. Warming will continue beyond the year 2100 under all RCP scenarios except RCP2.6. Warming will continue to vary across years and decades and will not be regionally uniform.
- Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions.

- Continued emissions of GHGs will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of these emissions.

The evidence of climate change continues to build and increasingly indicates that humans influence climate, including warming, extreme events, sea-level rise and melting sea ice. IPCC documents now use terms such as “very likely” or “virtually certain,” when describing climate change, where previous reports used “likely.” Over time there has been a gradual increase in confidence of the projections from climate models. With each IPCC report, more and higher-quality observations of climate change are possible, and improvements in model equations and their spatial and temporal detail improve climate projections. The IPCC reports continue to provide the best science-based information on projected climate change assembled from the best climate researchers worldwide. Climate change projections for Appendix B are based on the same new models used for guidance in the recent IPCC AR5 report.

B.3 PROJECTION METHODOLOGY

As demonstrated in Appendix A, there has been a gradual increase in temperature and precipitation in the TCWR area. This is consistent with the projections of climate models used in the IPCC assessments. Climate change projections indicate that these trends will continue regardless of the RCP considered; change will be greater with the higher RCP (8.5). The projections under the two RCPs begin to diverge significantly after the year 2050. The strongest indicators of vulnerability for the TCWR are based on temperature, so this variable was investigated in Appendix B. Using all available models and model runs (amounting to approximately 75 projections per RCP), changes in average temperature were determined. The use of the AR5 (CMIP5) ensemble allows for the calculation of an average projection of future climate that represents the consensus of all independent models. The projections for the variables in this report represent the best estimate available — and are more indicative of the general expectations of climate change than any single model is.

This study uses the delta method, which is a statistical approach to assessing multiple variables. It is the simplest and most easily interpreted methodology. The change in the models between a baseline period and future period are obtained, and this difference is then added to the observed baseline temperature. This method removes any bias that each model might have and considers only the degree of change. The baseline period considered here is 1981–2010, and projections were generated for the 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2100). Observed temperatures in the baseline period were then adjusted by the projected monthly changes to generate a new future temperature time series. This future time series was then used to calculate future parameters; e.g., number of freezing-degree days (FDD) and melting-degree days (MDD). The variability found in the historical period of 1981–2010 was assumed to be the same in future periods, since the addition of the "delta" would not change this baseline distribution. This is a reasonable approach, since there is no consensus on distribution change and the historical distribution over 30 years is likely to capture this variability.

Steps:

1. Obtain the baseline mean temperature used for the parameters.
2. Interpolate the IPCC AR5 models to the same resolution and calculate the mean temperature change for each month for each of the three future projection periods for the area covering the TCWR region.
3. Adjust the historical time series by the mean of all model change in temperature from the model projections.
4. Use the three future time period mean temperature time series to recalculate future parameters.

B.4 PROJECTED WINTER TEMPERATURE

The most recent normal period (1981–2010) for Yellowknife indicates an average wintertime (December-January-February) temperature of –23.5°C. Mean winter temperature for the baseline period is shown below in Figure B3.

As seen in Appendix A, winter temperature has increased from –26°C to –23.5°C. Monthly changes are greatest during January and February, with an increase of up to 3.1°C (Figure B4). The observed trend of increasingly warmer winters presents a long-term challenge to winter road operations. Model projections indicate that this observed trend is consistent with IPCC projections and will continue.

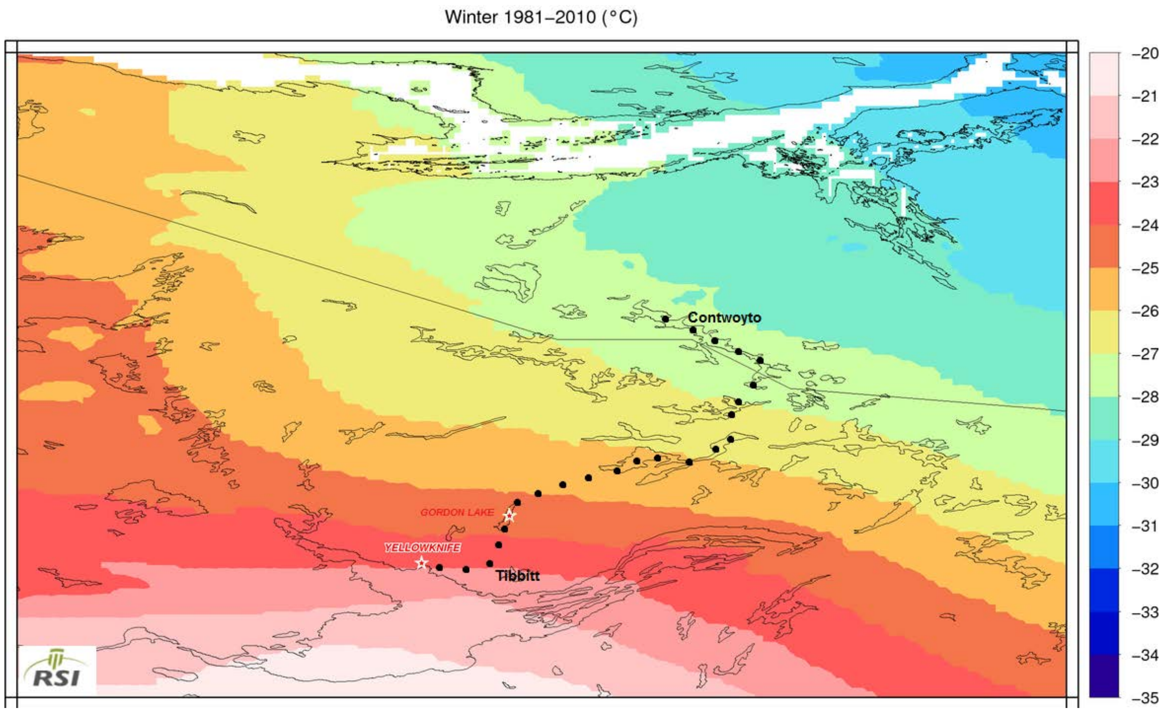


Figure B3: Mean winter (D-J-F) temperature (°C) along the TCWR, 1981–2010

Data source: McKenney et al. 2011

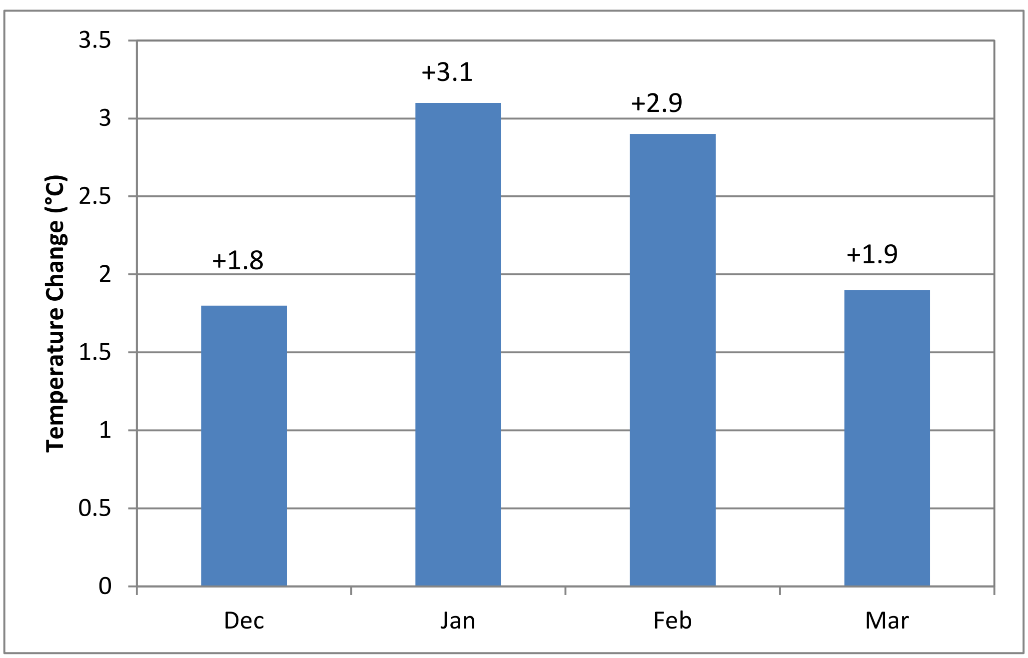


Figure B4: Change in monthly temperature normals at Yellowknife A (1942–1970 to 1981–2010)

Data source: Environment Canada 2014

From the AR5 multi-model analysis, future mean winter (D-J-F) conditions were obtained from the approximately 75 model runs for two emission scenarios: RCP4.5 (low emission), and RCP8.5 (high emission); see Figure B5. Not unexpectedly, greater warming is associated with the higher RCP8.5 emission scenario.

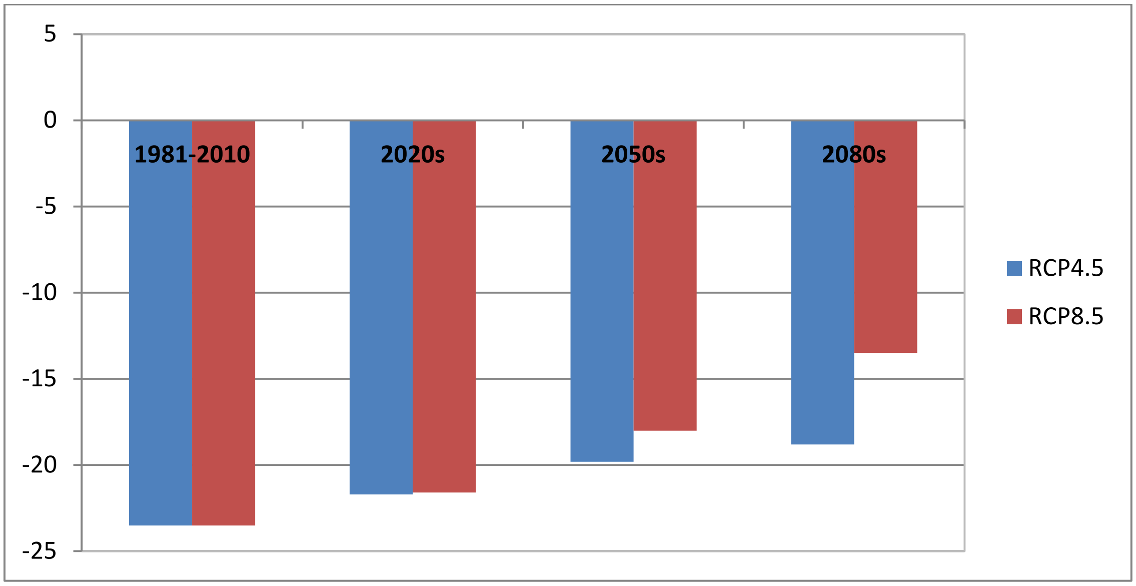


Figure B5: Mean winter (D-J-F) temperature projections at Yellowknife A (based on AR5 ensemble)

An important point to consider is that historically, emissions have followed the higher RCP8.5 emission pathway, so this could very well be the more probable trend for projected winter temperature (shown in Figure B3).

B.5 PROJECTED WINTER FREEZING-DEGREE DAYS (FDD)

In Appendix A, previous normal periods were used to provide the correlation between mean winter temperature and FDD accumulation. This robust association is shown in Figure B6.

As expected, accumulated FDD has decreased as winters have warmed. Using the regression association between mean winter temperature and FDD, projected FDD accumulation was estimated from the projected future winter temperatures for the two emission scenarios (Table B2). These results are shown in Figure B7.

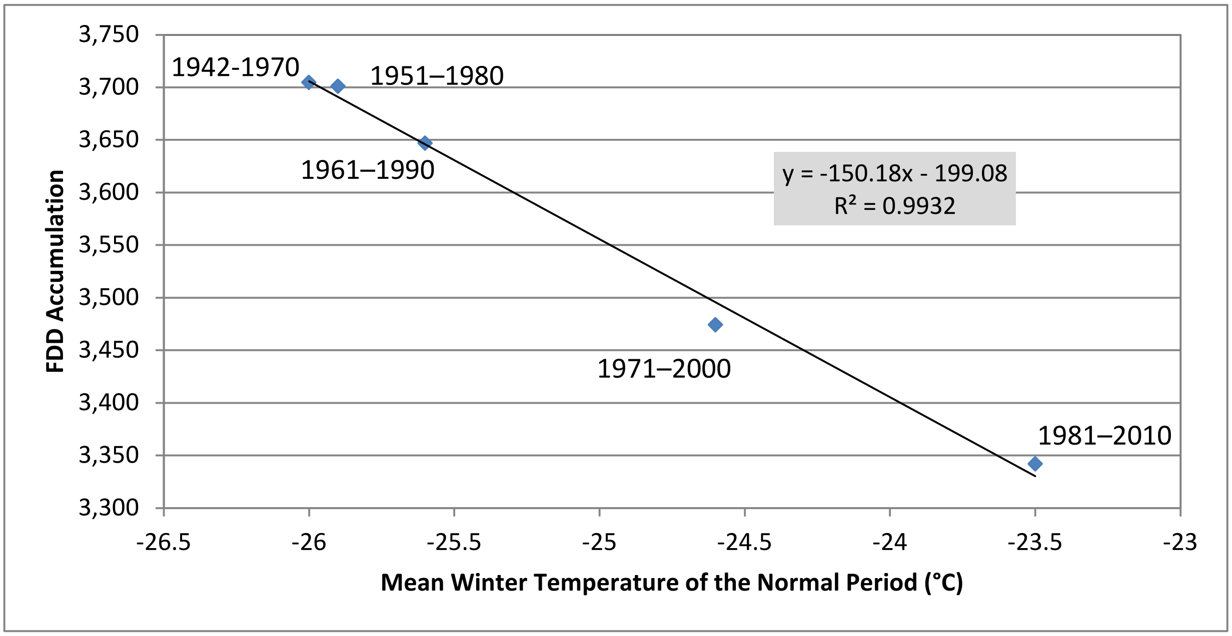


Figure B6: Correlation of historical FDD accumulation and mean winter temperature at Yellowknife A, 1942–2010

Data source: Environment Canada 2014

Freezing-degree day accumulation decreases from a minimum of 3,350 in 1981–2010 to 3,000 in the 2020s for both RCPs. From the 2050s on, projections diverge; the minimum FDD accumulation for RCP8.5 in the 2080s is half that observed in 1981–2010. These estimates are based on an overall change in mean winter temperature. Such a significant reduction would likely have a profound impact on winter road construction and maintenance.

Table B2: Projected ensemble winter (D-J-F) temperature and FDD accumulation

Time Period	RCP4.5		RCP8.5	
	°C	FDD	°C	FDD
2020s	–21.7	3,059	–21.6	3,045
2050s	–19.8	2,774	–18.0	2,504
2080s	–8.8	2,624	–13.5	1,828

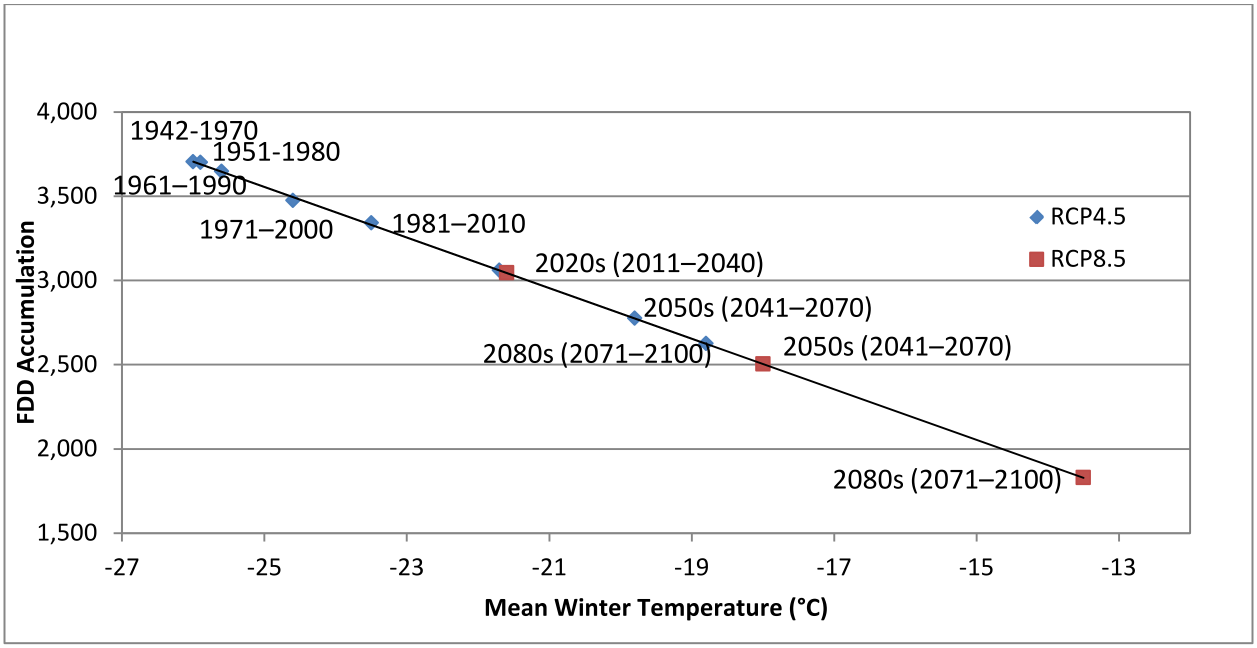


Figure B7: Historical and projected FDD accumulation vs. mean winter temperature for RCP4.5 and RCP8.5 for the 2020s, 2050s and 2080s

Data source: Environment Canada 2014

B.6 PROJECTED FDD AND WINTER ROAD OPERATING PERIOD

Based on the length of the winter road season since 1994 (JVMC 2013), the relationship between FDD accumulation and season length was determined. The correlation is not ideal, since there are factors beyond FDD that determine the road season length. Some of them are not linked to climate, such as the mining economy of that year, or the volume of materials that need to be transported, both of which can affect road closure. The association between the two variables is seen in Figure B8. A higher number of operating days is associated with higher FDD accumulation. Simply put, colder years lead to potentially more operating days.

This historical association can be extended using projected FDD accumulations under two climate change assumptions: low (RCP4.5), and high (RCP8.5). Projected operating days based on these assumptions are shown in Figure B9. Using a recent average operating season length (JVMC 2013), the length of the season gradually reduces due to increased warming. By the 2020s, warming from both scenarios reduces the average operating season to approximately 60 days, by the 2050s the length of the season ranges between 50 and 55 days, and by the 2080s the projections are between 38 and 52 days. As stated above, historical emissions have more closely followed the assumptions of the higher RCP8.5 scenario, making the greater reduction in operating season length more likely.

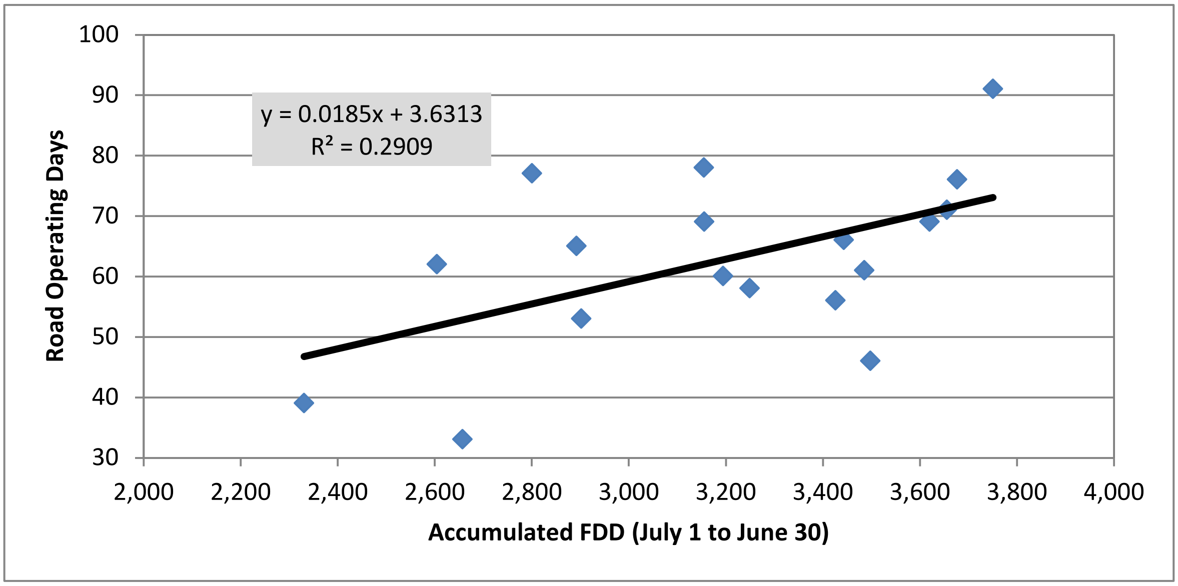


Figure B8: Comparison of operating days and FDD accumulation, 1994–2013

Data source: Environment Canada 2014, JVMC 2013

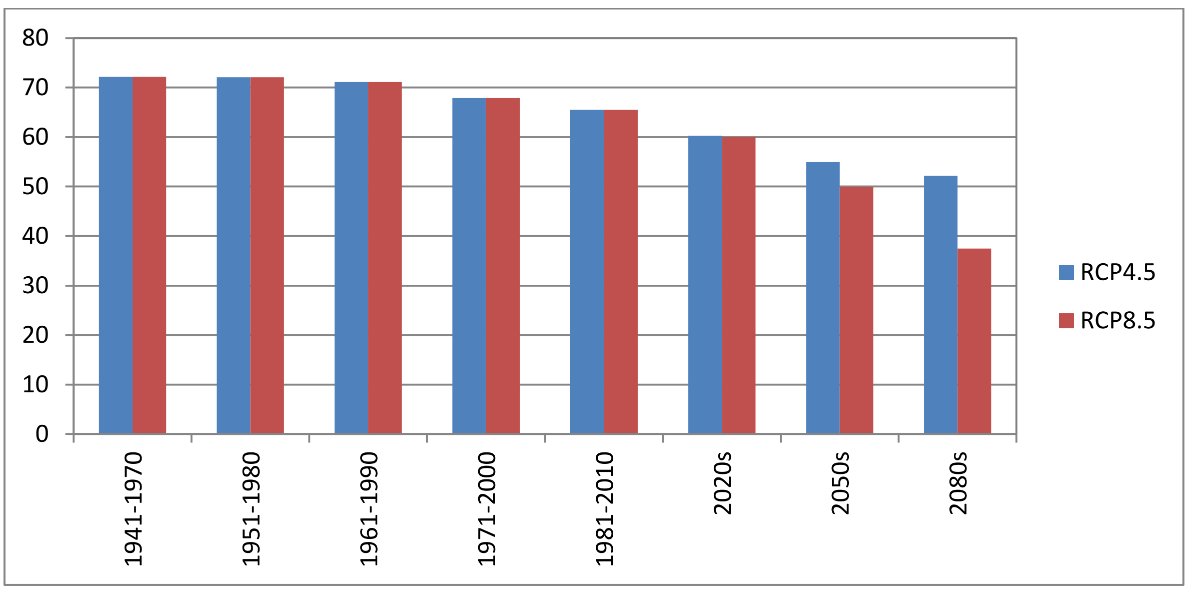


Figure B9: Projected operating season length for RCP4.5 and RCP8.5 (based on AR5 ensemble)

Additional adaptation actions in road construction may help to mitigate this change, but these are not considered in this purely climatological analysis. The relationship between accumulated FDD and operating season length also does not consider the accumulation of melting-degree days (MDD), which would shorten the season length even more (see section B.8).

B.7 PROJECTED DATE OF ACCUMULATED FDD AT 300

As noted in Appendix A, Kuryk (2003) indicates that the accumulation of FDD to 306 signifies a date at which the ice should be thick enough for winter road construction to begin. From the ice thickness formula provided in A.2.2.2, 300 FDD corresponds roughly to an ice thickness of 25 cm. This would provide enough strength to support the start of construction. Therefore, for each year in the record the date at which the FDD accumulation reaches 300 was determined. Once again, this indicator does not consider other factors that influence road construction. For this variable, the accumulated FDD used is for the previous year (i.e., the data shown for the 1971 winter road year is actually from 1970, when the ice formed). Theoretically, the earlier the threshold of 300 FDD is reached, the earlier that winter road construction can begin, so colder falls/early winters lead to earlier starts. The dates of the 300 threshold are shown below in Figure B10. These are shown as days after November 1.

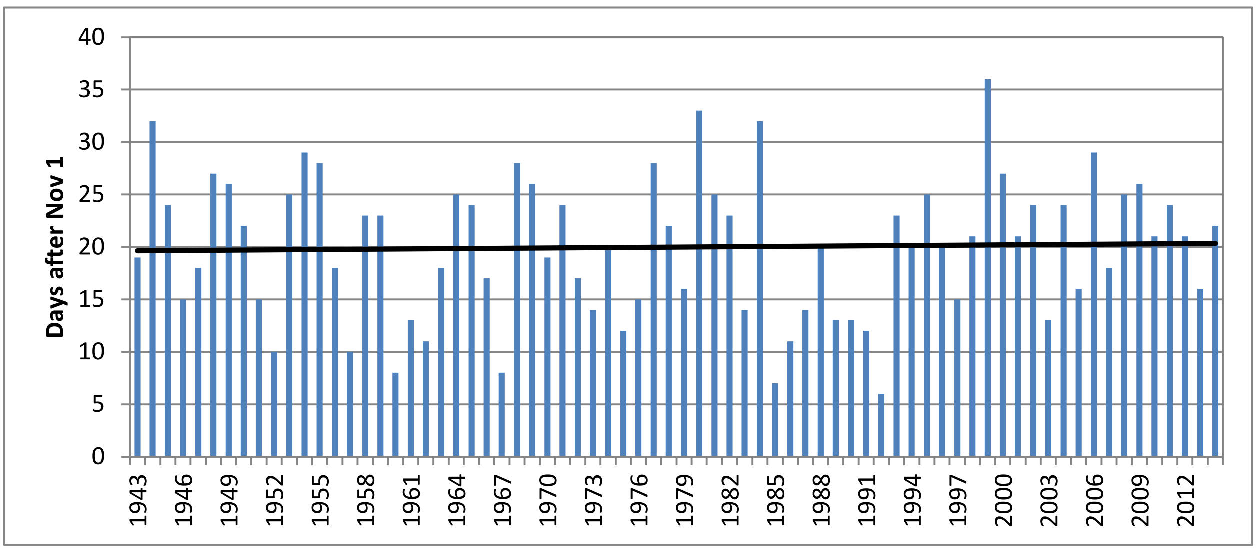


Figure B10: Days after November 1 (of previous year) for FDD accumulation of 300 at Yellowknife A, 1943–2013

Data source: Environment Canada 2014

Notably, there appears to be no clear trend in the date of accumulation of 300 FDD over the full period. The average date is November 20. It has been as early as November 6 (the 1992 winter road season, which corresponds to 1991 ice formation), and as late as December 15 (the 1999 winter road season, which corresponds to 1998 ice formation). For the shorter, more recent, normal period of 1981–2010 (Figure B11), there appears to be a trend for later FDD300 that is not present in the longer term. The date of FDD300 is eight days later over this shorter period. This would indicate a more recent trend of accelerated warming.

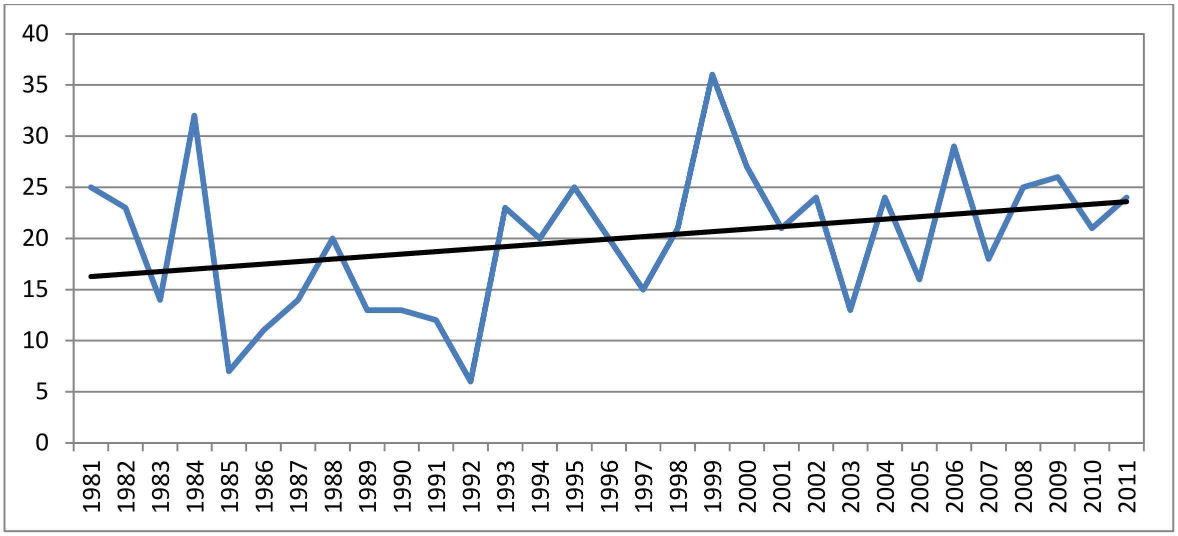


Figure B11: Trend in days after November 1 for FDD accumulation of 300 at Yellowknife A, 1981–2011

Data source: Environment Canada 2014

Applying the AR5 ensemble model to average monthly change in temperature and adding this to the baseline 30-year period daily values, the projected FDD300 date can be calculated. The projected dates for the two RCPs are provided in Figure B12, showing the change in this threshold based on an average of all models.

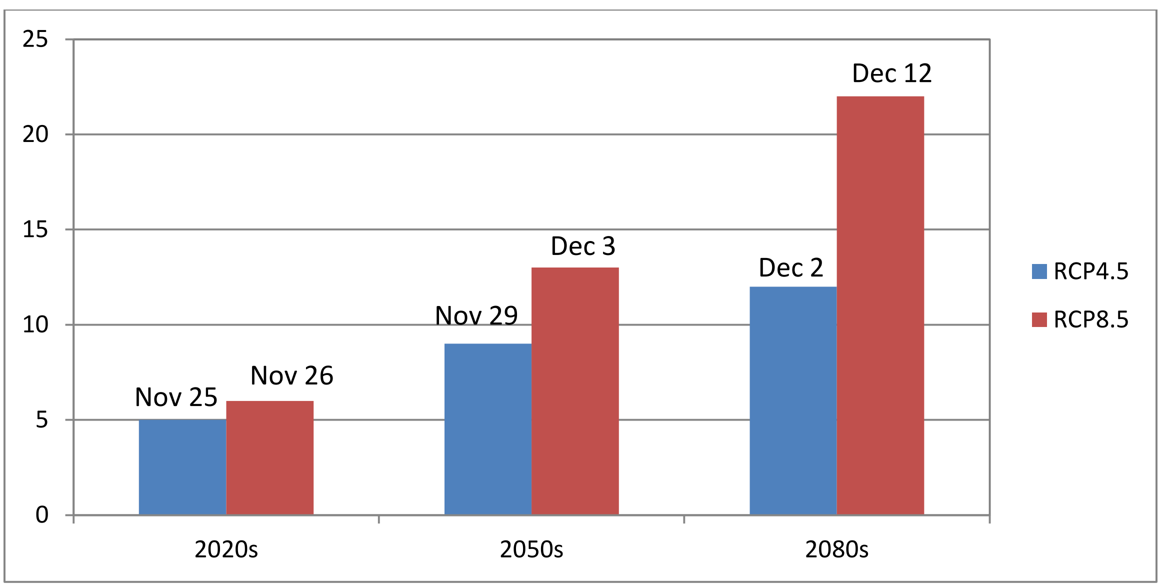


Figure B12: Projected change in date of FDD300 threshold from 1981–2010 baseline of November 20

Based on AR5 ensemble

B.8 PROJECTED MELTING-DEGREE DAYS (MDD)

This variable serves as an indicator for the potential closing of the winter road due to the accumulation of heat from days with a mean temperature greater than 0°C. The summation is started on January 1 of each year; the MDD value reached as of April 30 (which is beyond the TCWR typical closure date) is plotted in Figure B13.

Over time, warming winter seasons have led to a gradual increase in MDD, which would tend to lead to earlier closure of the winter road. Notably, a very high MDD occurred in 2010, which corresponded to an early closing date for the road (JVMC 2013); this is the outlier to the right in Figure B13.

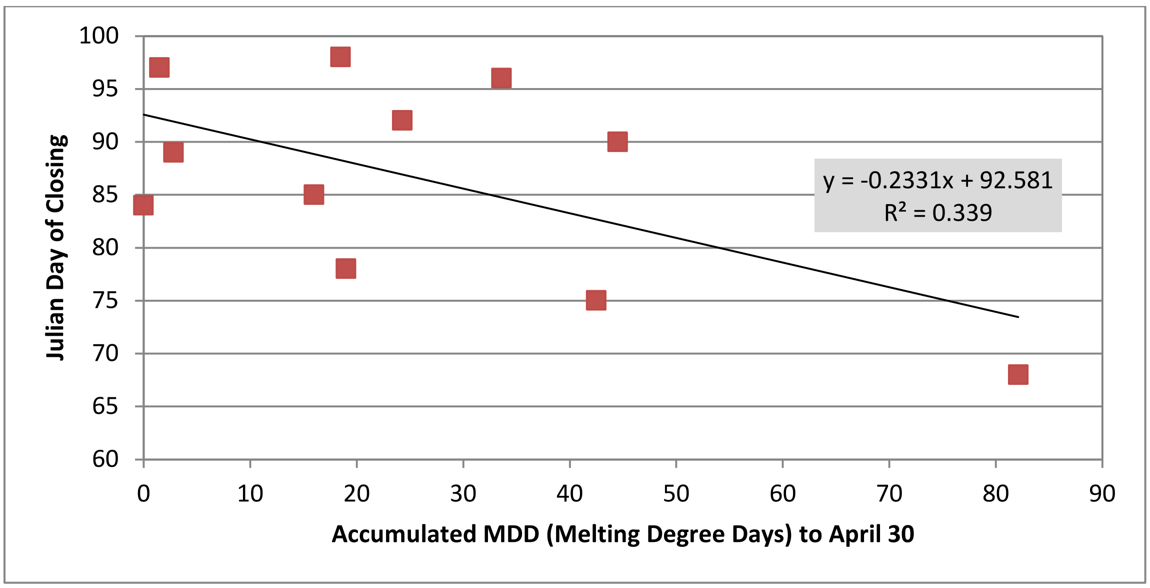


Figure B13: MDD accumulation and Julian day of road closure at Yellowknife A

Data source: Environment Canada 2014

Average MDD in the 1981–2010 baseline period is shown in Figure B14, along with the projected MDD values, which were calculated using both RCP4.5 and RCP8.5 projections. These were obtained by adding the projected change in temperature from the model ensemble to the baseline period daily values and then recalculating the MDD accumulation. MDD values have typically been quite low — approximately 25 — but are projected to increase under both scenarios.

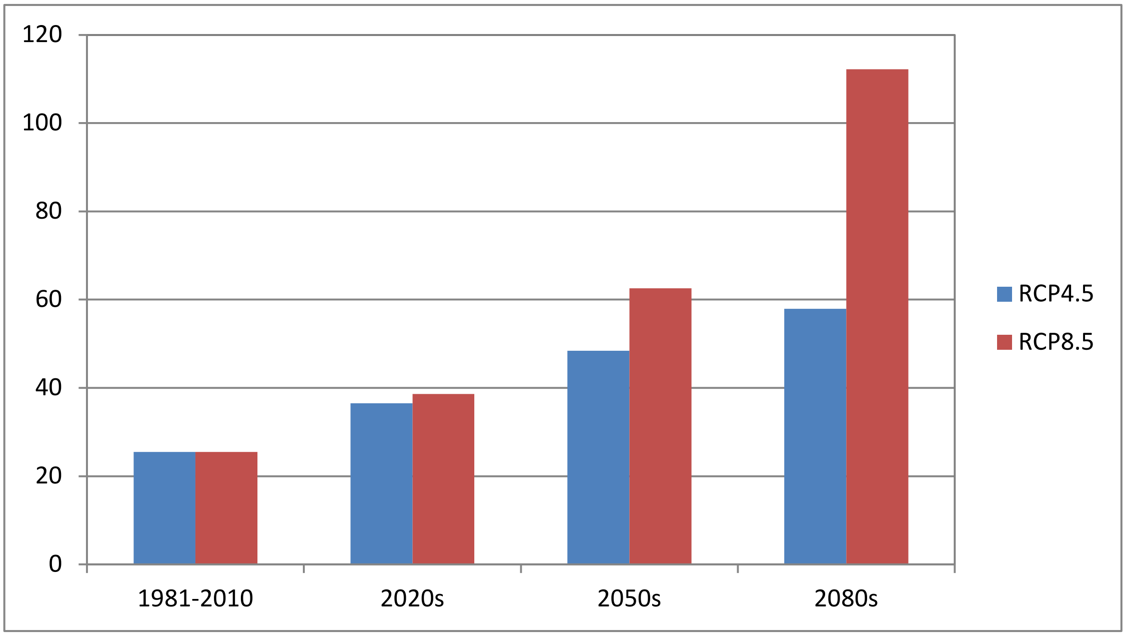


Figure B14: Projected change in MDD January 1 – June 30, 1981–2080s

Based on AR5 ensemble

From the historical relationship between MDD and the closing date of the road (shown in Figure B13), future closing dates may be estimated from future average MDD accumulations. This is shown in Figure B15. Both scenarios shorten the season by about a week by the 2050s and by one to three weeks by the end of century. The trend of increasing MDD is supported by the long-term pattern shown in Figure A13. Average MDD values have increased very gradually, from 18 to their current levels, but are highly variable from year to year, ranging from near zero to as high as 92. All but the highest MDD values (RCP8.5 in the 2080s) fall within the observed range of MDD since 1943. MDD changes are relatively small compared to FDD changes, and therefore result in smaller changes to projected closure dates.

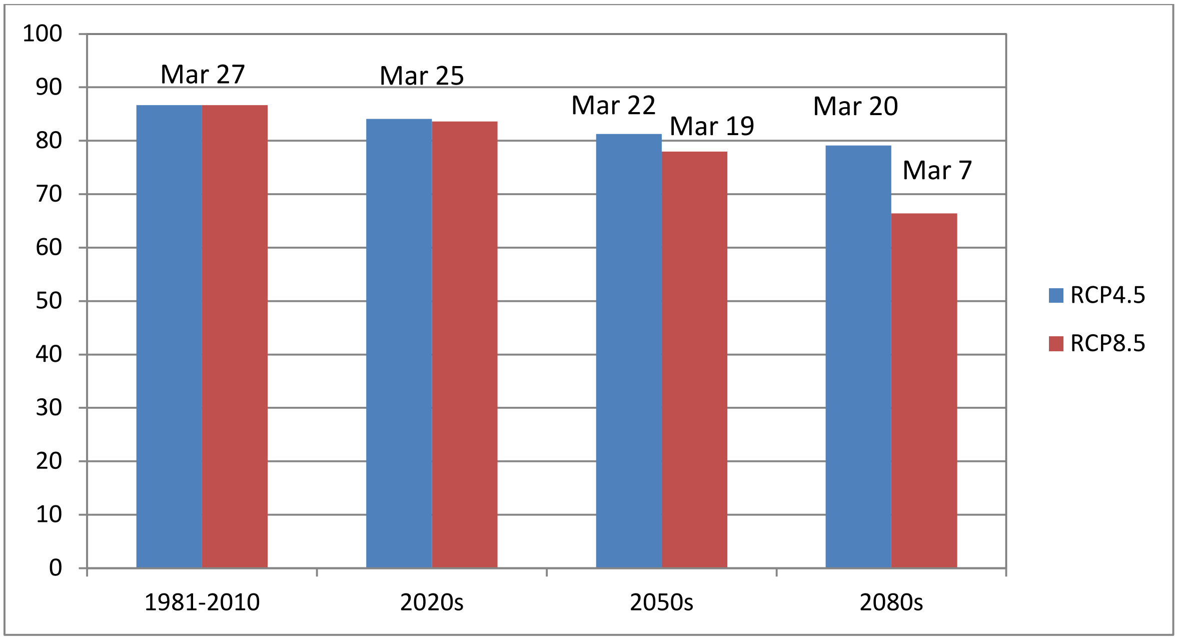


Figure B15: Projected average road closing date based on MDD accumulation

Based on AR5 ensemble

B.9 CONCLUSIONS

The greatest factor in the TCWR season is thermally controlled, so winter temperatures and the accumulation of freezing-degree days (FDD) and melting-degree days (MDD) are considered here. Appendix B used a baseline condition and then applied the AR5 model ensemble of projected temperature change to this baseline. The AR5 model ensemble allowed for projections of the most likely future conditions. The use of ensemble averages from many models from IPCC (2013) provided the best basis for this analysis. Calculations using future temperatures were then used to estimate future accumulated FDD and MDD, length of the operating season and other critical information.

Not surprisingly, all indications under a warming climate point to greater challenges for winter road construction and operation. A reduction in FDD and a resulting delay in winter road formation and shortening of the winter road season are projected. In addition, an increase in MDD in the spring will also lead to an earlier closure of the road. The operating period is projected to be affected by both later opening dates and earlier closing dates. Both later starts and earlier closures are driven purely by temperature. The current average season length of 65 days is projected by all indications to be reduced by lower FDD in the fall and winter and higher MDD in the spring. This is projected to result in an average operational period of 43 days in the 2050s (Figure B16). Beyond the 2050s, projection scenarios diverge significantly; the reduction in season length ranges between 15 and 45 days when the net effect of decreasing freezing-degree days in the fall and increasing melting-degree days in the spring is considered.

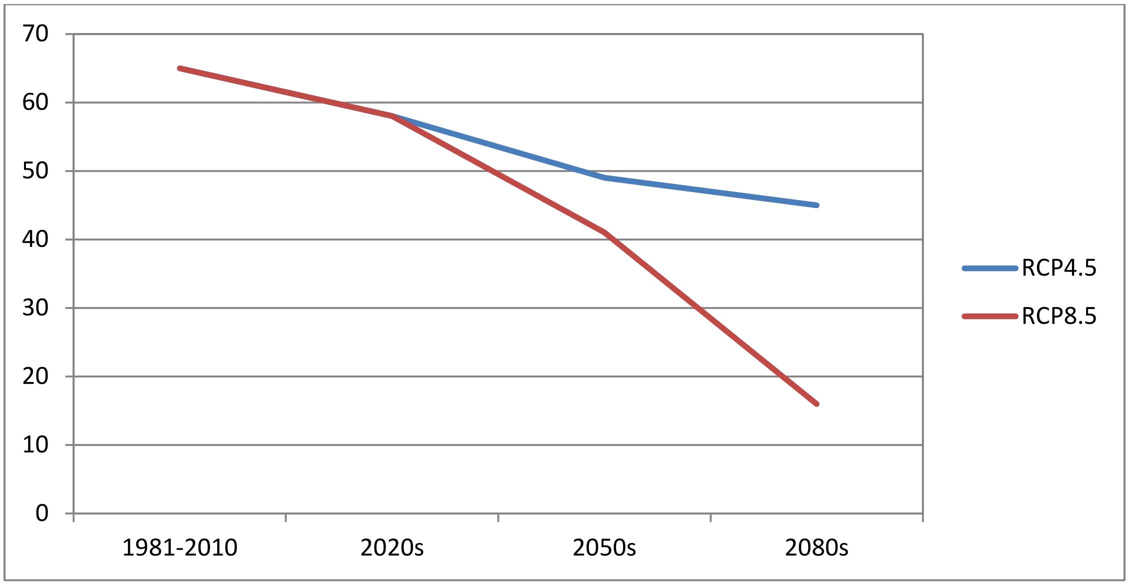


Figure B16: Estimated number of operational days based on decreased FDD and increased MDD

Based on AR5 ensemble

These projections are based on the historical relationships between FDD and MDD and on data related to season length, start dates and end dates. These relationships are not precise and could be further refined with more data on historical start and end dates. The main point, however, is that increased warming will undoubtedly lead to significant changes in winter road sustainability. This is due to later fall freezing and earlier spring melting. Improved monitoring and road construction techniques may address some of the seasonal reductions indicated here, but the challenges going forward are all projected to increase for ice roads in the North.

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