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The impact of climate change on a large industrial winter road operation in Northern Canada

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ABSTRACT

Winter roads are essential seasonal transportation routes for communities and industries in sub-arctic regions; however, their operational viability is threatened by climate change. Canada has the longest winter road in the world, the Tibbitt to Contwoyto Winter Road (TCWR). This paper uses Freezing Degree Days (FDD) as a key indicator for the opening dates and the cumulative downward surface thermal radiation for the closing dates of the TCWR. By analysing changes in temperature and cumulative downward surface thermal radiation, we observe alterations in the opening and closing dates, ultimately shortening the operational period of the TCWR. A shortened operational period will lead to no viable operations by 2080 and the disappearance of the TCWR before the end of the 21st century. With the TCWR gone, there will be a significant social and economic impact on the region, resulting in job losses and a contraction in GDP in Canada's Northwest Territories.

1. Introduction

According to the 21st Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), also known as the Paris Agreement, the world's nations have committed to reducing global greenhouse gas emissions to keep the temperature rise below 2 °C, while aiming to limit the increase to 1.5 °C above pre-industrial levels (UNFCCC, 2015). Although many governments have outlined strategies to address climate change, implementing these plans remains a significant challenge. Despite their pledges, most initiatives lack detail, accountability measures, and sufficient resources. Economic and financial limitations further hinder efforts, reducing the ability to turn policy into real progress towards emission cuts and climate goals (Stankovic et al., 2023). All governments must strengthen their Nationally Determined Contributions (NDCs) to reach carbon neutrality and curb global temperature increases (Huang and Zhai, 2021).

Glaciers and ice sheets near the Arctic Circle are melting due to rising global temperatures (Hori et al., 2018a). Similarly, road infrastructure in the Arctic areas has also been disrupted by climate change. Winter roads are seasonal transportation routes and an essential supply line for remote communities and industries, particularly in regions where permanent roads are not feasible (Barrette, 2015; Hori et al., 2018b). The disruption of the operational period for winter roads can severely impact these remote communities, as they are compelled to rely on alternative transportation methods such as tugboats, barges, or air freight. These options are considerably more expensive, increasing the costs of everyday goods and essential supplies. For instance, in some northern communities, perishable items like oranges may cost as much as $5 CAD each due to the high expenses associated with air transport, highlighting the significant economic burden placed on residents when overland supply chains are interrupted.

In the Northwest Territories of Canada, freight movement depends on a combination of transportation modalities, including air, water, and seasonal winter roads (Government of Northwest Territories, 2015). However, each modality possesses its own seasonal, economic, and logistical constraints. Air transportation facilitates year-round services; however, it is costly and limited in transporting substantial quantities of heavy industrial equipment (Transport Canada, 2016). Marine transportation, such as barge operations, is cost-effective when accessible, but it is contingent on geographic, seasonal, and water-condition factors (Government of Northwest Territories, 2015). Within this comprehensive transportation framework, winter roads are essential for providing relatively economical conveyance of bulk equipment, fuel, and vital supplies to remote communities and industrial sites within the region.

As shown in Fig. 1, Canada has approximately 10,000 km of winter roads, more than any other country worldwide (Barrette and Charlebois, 2018). The Tibbitt to Contwoyto Winter Road (TCWR) holds the title of the longest winter road in the world, stretching 400 km from Tibbitt Lake to the Ekati Diamond Mine, measuring 50 m wide on ice and 12 to 15 m wide on portages (Tibbitt to Contwoyto Winter

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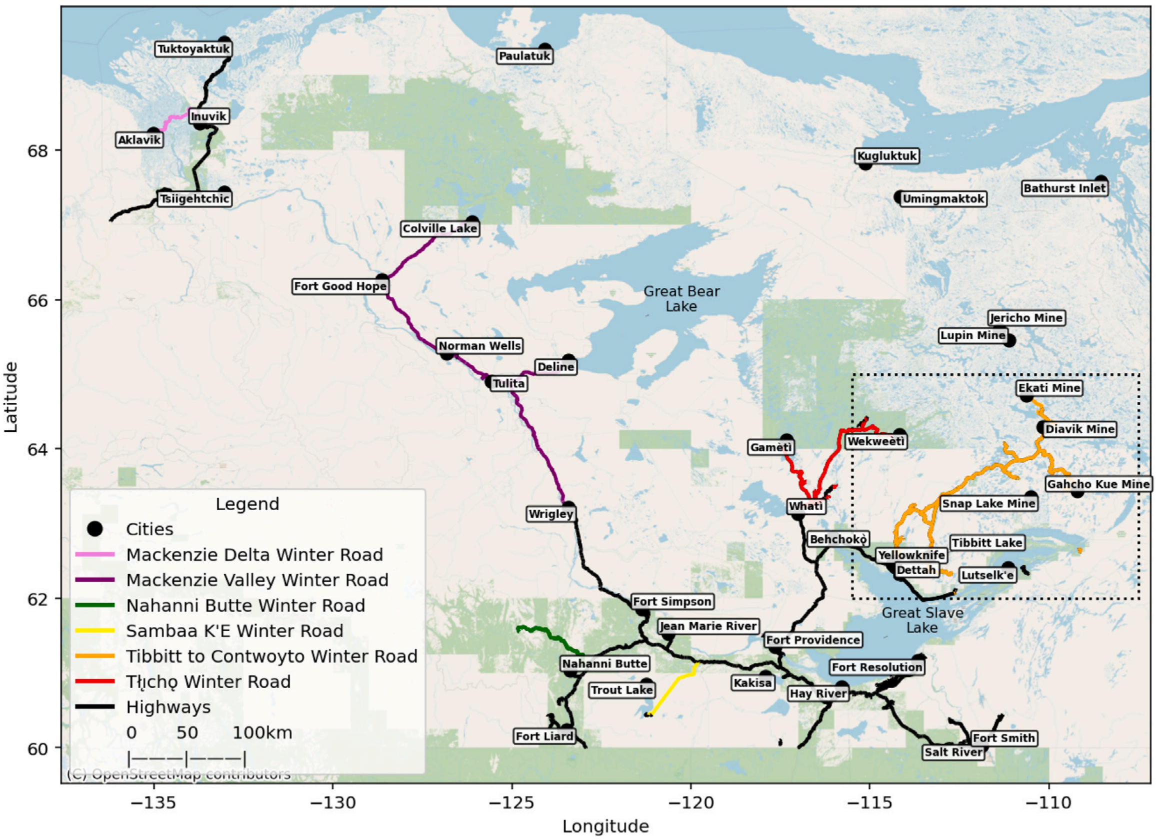

Fig. 1. Map of winter roads in Northern Canada (Government of Canada, 2024).

Road Joint Venture, 2025a). The TCWR is a private seasonal route first constructed in 1982 to supply the Lupin Gold Mine at Contwoyto Lake, Nunavut Territory, with heavy machinery and equipment (Barrette, 2011). Although it remains primarily used for transporting heavy machinery and equipment to the diamond mines in the region, it has also been utilised over the years to deliver supplies to other sites in the area (Mullan et al., 2017).

Unlike the locations of certain winter roads, such as the Mackenzie Valley Winter Road, the terrain does not support the development of a permanent highway, like the Mackenzie Valley Highway that is under planning. 87% of the TCWR is built over lakes or watercourses, while the remaining 13% crosses overland portages, heavily relying on ice formation as a result, permanent road infrastructure development is unfeasible (Tibbitt to Contwoyto Winter Road Joint Venture, 2001). Consequently, the rise in global temperatures and shifting freeze-thaw cycles have delayed its opening dates and shortened operational periods, leading to logistical and economic challenges for stakeholders and policymakers (Barrette, 2011).

Current research has utilised traditional temperature-based indicators, such as Freezing Degree-Days (FDD), calculated as the cumulative sum of sub-zero daily temperatures, to estimate winter road conditions (Vermette and Christopher, 2013). Different studies indicated that when the FDD value reaches 305–1100, winter road construction can begin (Sladen et al., 2020). While air temperature and downward surface thermal radiation are key factors influencing many aspects of winter operations, other considerations also play a role. The most critical factor affecting the TCWR's opening date is the requirement for an ice thickness of 30 cm before construction of the winter road can begin (Sladen et al., 2020). The first step is to deploy ground-penetrating radar (GPR) to measure ice thickness (Tibbitt to Contwoyto Winter Road Joint Venture, 2025a). If the appropriate ice thickness is achieved by removing snow from frozen lake surfaces, it is essential to note that snow acts as an insulator, slowing ice formation. The snow must be removed to enhance heat loss from the ice surface and promote faster and more uniform ice growth. Following snow removal, artificial ice thickening is implemented through flooding techniques utilising low-head, high-volume pumps to extract water from beneath the ice surface. The extracted water is then spread over the water surface across the roadway alignment, where it solidifies in successive layers. In this process, the operator drills holes along the road at regular intervals. Water is then drawn from these holes using a low-head pump, spread over the road surface, and solidifies into a thin layer on the ice; this procedure is repeated several times, adding layers of water that will freeze into ice, with up to 0.60 m of ice potentially required to ensure the road can sustain large vehicles transporting heavy machinery.

Auger drilling and ground-penetrating radar (GPR) are employed for daily monitoring to ensure that ice thickness is adequate to support large vehicles and maintain road safety (Annan et al., 2015). The winter road cannot be officially opened until it reaches an ice thickness of 74 cm, at which point it can sustain light vehicles, and as the ice thickness increases to 100 cm, the winter road reaches full-load capacity to support heavy transport vehicles (Tibbitt to Contwoyto Winter Road Joint Venture, 2025a). Artificial flooding is also employed for road maintenance where necessary and where the ice cover has been compromised. This water is then spread and allowed to freeze in layers. Ice thickness measurements are repeated throughout the TCWR's operational period, alongside artificial thickening, to ensure safe and viable road use.

The minimum viable operational period of the TCWR is 45 days, as any duration shorter than this is not economically feasible (Mullan et al., 2017). Historically, the average operational period of the TCWR has been 67 days, with on average 8336 truckloads (281,363 tons) travelling across it annually (Collins and Kumral, 2020; Mesher et al., 2008). Rising global temperatures and increased downward surface thermal radiation have delayed opening dates and moved closing dates earlier, resulting in shorter operational periods (Mullan et al., 2021).

These shortened operational periods have caused logistical and economic challenges for stakeholders and policymakers (Woolway et al., 2022). Perhaps in the future, if the 100 cm ice thickness cannot be achieved, fewer and smaller loads may be required. The opening dates are more affected than the closing dates because the opening date depends heavily on the minimum ice thickness, which can be difficult to achieve; however, once achieved, it is much easier to maintain. Therefore, the closing date is not impacted as significantly by climate change as the opening date.

This paper utilises the temperature-based indicator FDD to estimate the winter road operational windows. However, temperature alone cannot fully capture the complex interactions that govern ice thickness and stability. A novel approach that utilises accumulated downward surface thermal radiation may significantly impact the timing of road closures.

Downward surface thermal radiation is the flow of infrared energy emitted by Earth's atmosphere and reaching the surface (Chen et al., 2024). This radiation is reflected from atmospheric components such as water vapour, clouds, and greenhouse gases, which emit it continuously, regardless of solar illumination (Khorsandi et al., 2023). Downward surface thermal radiation is a key component of the surface energy balance, particularly during winter in cold regions, where shortwave solar radiation is minimal or absent. Downward surface thermal radiation plays an important role in the operational viability of winter roads, as operability is strongly linked to the thermal stability of ice surfaces (Zhang et al., 2021). While ambient temperature is a key component of ice formation, ice degradation is dominated by radiative energy. Evidence indicates that the largest contribution, approximately 82% during cold seasons, is downward surface thermal radiation, which melts ice in the Arctic region (Zhang et al., 2021). However, the use of this meteorological variable to assess the closing date of the winter road has not previously been applied.

Using that approach, a prediction of the viable operational period, this paper discusses the future of the TCWR from the perspective of the opening and closing dates at which the viable operational period will end. Considering the climatic factors that affect road opening and closing dates is crucial for effective planning and risk management, helping policymakers better adapt to the impacts of climate change on the TCWR (Mesher et al., 2008).

Other methods were attempted to determine the opening and closing dates of the TCWR. These methods include using a FDD of 305 °C-days plus 42 days. Fig. 2 demonstrates that a FDD of 305 °C-days plus 42 days predicts the opening dates too early compared to the actual opening dates. Additional methods involve using temperature-based indicators, such as Thawing Degree-Days (TDD), downward surface solar radiation, surface net solar radiation, snow depth, and precipitation, to estimate winter road conditions; however, none of these methods produced accurate results. TDD is calculated as the cumulative sum of above-zero daily temperatures (Boyd, 1976). This method results in a TDD of 10 °C-days plus 8 days. Fig. 2 indicates that the projected closing dates are significantly later than the actual closing dates (Kanigan, 2008). These unsuccessful methods utilise the literature-suggested mechanisms for opening and closing dates.

The main contribution of this paper lies in applying a robust climate attribution methodology to assess the impact on operations of an example large industrial winter road in Northern Canada, the TCWR. By employing the World Weather Attribution (WWA) 8-Step Event Attribution Protocol to define and validate thresholds that determine the opening and closing dates, the operational period is established. Applying these threshold values to future climate scenarios provides valuable insights into the potential influence of climate change on the operational periods of the TCWR.

The remainder of this paper is organised as follows: Section 2 describes the data sources and methodology employed in the study. Section 3 presents key findings from the models and simulations regarding the future TCWR operational period. Section 4 discusses the implications of these findings for winter road management and climate adaptation. Section 5 provides recommendations for future research and policy.

2. Methods

Refer to Fig. 1, which illustrates the study area, the Northwest Territories of Canada, showcasing the winter roads in Northern Canada.

2.1. Datasets

We require multiple datasets to accurately develop and verify our model, which will determine the opening and closing dates for the TCWR.

In Fig. 2, the first dataset utilised is the Northwest Territories Winter Roads, Ice Roads, and Ice Crossings - Historical Open and Close Dates, published by the Northwest Territories Government (Government of Northwest Territories, 2025). This dataset serves as the foundational baseline around which all the other datasets will revolve (Government of Northwest Territories, 2025).

The second dataset comprises the ERA5 hourly data on single levels from 1940 to the present. ERA5 is the fifth and latest generation of European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, providing data from 1940 onwards for global climate and weather over the past decades (Copernicus Climate Change Service, 2025). With the spread and members set at 0.5° × 0.5° (atmosphere) and 1° × 1° (ocean waves), the reanalysis's horizontal resolution is, on average, 0.25° × 0.25° (atmosphere) and 0.5° × 0.5° (ocean waves) (Copernicus Climate Change Service, 2025).

To verify the accuracy of the newly developed model and the ERA5 datasets, two additional datasets have been selected from the Centre for Environmental Data Analysis (CEDA) archives (Townsend and Wilkinson, 2021). The datasets obtained from CEDA have also been used to project future opening and closing dates of the TCWR.

The Hadley Centre Global Environment Model version 3 (HadGEM3) represents a model family comprising several distinct configurations, each based on a common physical framework but varying in complexity. These configurations feature a linked atmosphere-ocean model that extends vertically to effectively capture a well-resolved stratosphere, along with an Earth System version that accommodates dynamic vegetation, ocean biogeochemistry, and atmospheric chemistry (Andrews et al., 2020).

The second dataset is the U.K. Earth System Model 1 (UKESM1). The UKESM1 is a new climate model with enhanced representations of atmospheric, oceanic, and terrestrial processes (Sellar et al., 2019).

The decision to select HadGEM3 and UKESM1 was based on the fact that these two datasets include the temperature variable for the opening dates and the downward surface thermal radiation variable (Downwelling Longwave Radiation) necessary for the closing dates. Furthermore, both datasets covered the appropriate time frame to project future operational periods from 2015 to 2100.

The horizontal resolution of the HadGEM3-GC31-MM model for the atmosphere and land is ≈60 km (N216, 0.83° lat × 0.55° lon), and the horizontal spacing for the ORCA025 grid is 0.25° (≈25 km) for the ocean and sea ice (Andrews et al., 2020). The horizontal resolution of the UKESM1-0-LL model for the atmosphere and land is ≈140 km (N96, 1.25°), and the horizontal spacing for the ORCA1 grid is 1° (≈100 km) for the ocean and sea ice. Both HadGEM3 and UKESM1 models utilise 85 vertical levels in the atmosphere, while the ocean components employ 75 vertical levels (Sellar et al., 2020).

2.2. Operational simulation model methods

There are three main steps to developing the TCWR simulation model. Step 1 involves plotting the historical opening and closing dates of the TCWR. Step 2 processes the raw ERA5 temperature data to establish the opening dates. Finally, Step 3 processes the raw ERA5 surface thermal radiation downward data for the closing dates.

Step 1: Compilation of Actual Opening and Closing Dates

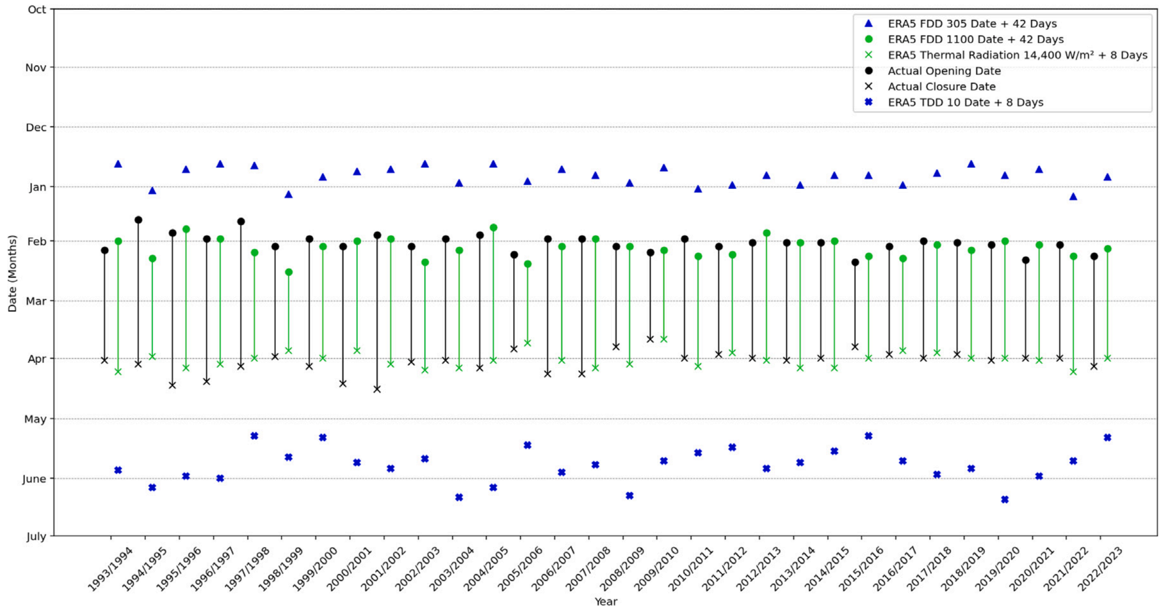

Fig. 2. The Northwest Territories Winter Roads, Ice Roads, and Ice Crossings – Historical Open and Close Dates and the ERA5 Modelled Opening and Closing Dates. The graph's y-axis displays the months, starting with November at the top and descending to May of the following year. The x-axis represents the years from 1993/1994 to 2022/2023. A black line connects the Actual Opening and Closing Dates, while a green line connects the modelled ERA5 Opening and Closing Dates. The blue data points represent unsuccessful attempts to utilise the literature-suggested mechanisms for opening and closing dates.

The government of the Northwest Territories has published a comprehensive dataset titled "Northwest Territories Winter Roads, Ice Roads, and Ice Crossings – Historical Open and Close Dates (1993–2023)". This dataset provides verified records of operational periods for key winter transportation routes over three decades. The opening and closing dates derived from this dataset are plotted in Fig. 2 and serve as the foundational reference for this analysis. All subsequent datasets and comparisons are anchored to these official records, ensuring consistent and accurate temporal alignment of observations.

Step 2: ERA5 Temperature Dataset Calculations

Before extracting data from ERA5, the coordinates for sub-region extraction were set to latitude bounds of 65.58°N to 62.27°N and longitude bounds of 114.11°W to 108.53°W. The time interval was selected for extraction, covering all months of each year, all days of each month, and every hour of each day (Copernicus Climate Change Service, 2025). By extracting the 2 m above surface temperature from ERA5, we can determine the Freezing Degree Days (FDDs). The FDD is a metric that assesses the intensity and duration of sub-freezing temperatures, which are critical for ice formation and the thickening needed for winter road construction and maintenance. FDDs are derived by counting the difference between 0 °C and the daily mean temperature on days when temperatures drop below the freezing point:

$$\mathrm{FDD} = \sum_{i=1}^{n} \left(0\ ^{\circ}\mathrm{C} - T_{\mathrm{avg},i}\right) \tag{1}$$

Through Eq. (1), where T_{avg} is the average daily temperature, this measure has been frequently used to assess the structural integrity and weight-bearing capacity of ice surfaces, particularly those found on lakes and tundra, which are critical for winter roads in the Arctic regions.

To initiate construction of the winter road, a ground freezing of 30 cm is required to ensure safe support for heavy-haul vehicles (Sladen et al., 2020). Conventionally, an FDD threshold of 305 °C days was recommended; however, it was observed that most winter road portages did not achieve the 30 cm frozen depth at this threshold, resulting in premature construction and unreliable opening dates (Sladen et al., 2020). A more cautious approach is initiating the construction of TCWR upon reaching an FDD threshold of 1100 °C days (Sladen et al., 2020). At this threshold, a 30 cm depth is established throughout the entire route, thereby providing a more reliable and stable foundation for the development of the winter road (Sladen et al., 2020).

FDD accumulation commences annually on 1st July, a date selected as a meaningful benchmark for the total freezing period. By midsummer, the ice from the previous winter will have fully melted, ensuring no residual freezing or carry-over from the last winter, thereby effectively resetting the measurement (University of Washington Polar Science Center). Once the threshold is met, the winter road requires 6 weeks (42 days) of construction time, including snow removal, flood control, and ice thickening along the entire route (Sladen et al., 2020).

Step 3: ERA5 Surface Thermal Radiation Downward Dataset Calculations

The downward surface thermal radiation effectively estimates the closing date of winter roads because it directly relates to energy input from the sun, the primary driver of the physical processes involved in the evolution of a winter road in late winter and early spring.

By extracting the surface thermal radiation downward variable from ERA5, we can determine the cumulative threshold needed to announce the closing date of the TCWR (Copernicus Climate Change Service, 2025). Downward surface thermal radiation exhibits a seasonal cycle in the Arctic, with a minimum typically in early January (Mlynczak et al., 2011). Consequently, 1 January was selected as a fixed reference point for quantifying the total radiative energy contributing to ice melting, as it provides a consistent baseline for calculating accumulated downward surface thermal radiation (Boccolari and Parmiggiani, 2017). From 1 January, an increment of 150 W/m^2 is added each day, culminating in a total of 14,400 W/m^2, plus an additional 8 days during which the new dates precisely align with the closure dates with those published by the Government of the Northwest Territories.

TCWR Operational Model

After determining the opening dates based on the FDD 1100 °C-days plus 42 days and the closing date, surface thermal radiation accumulates to 14,400 W/m^2 plus 8 days. The modelled opening and closing dates align with the actual opening and closing dates.

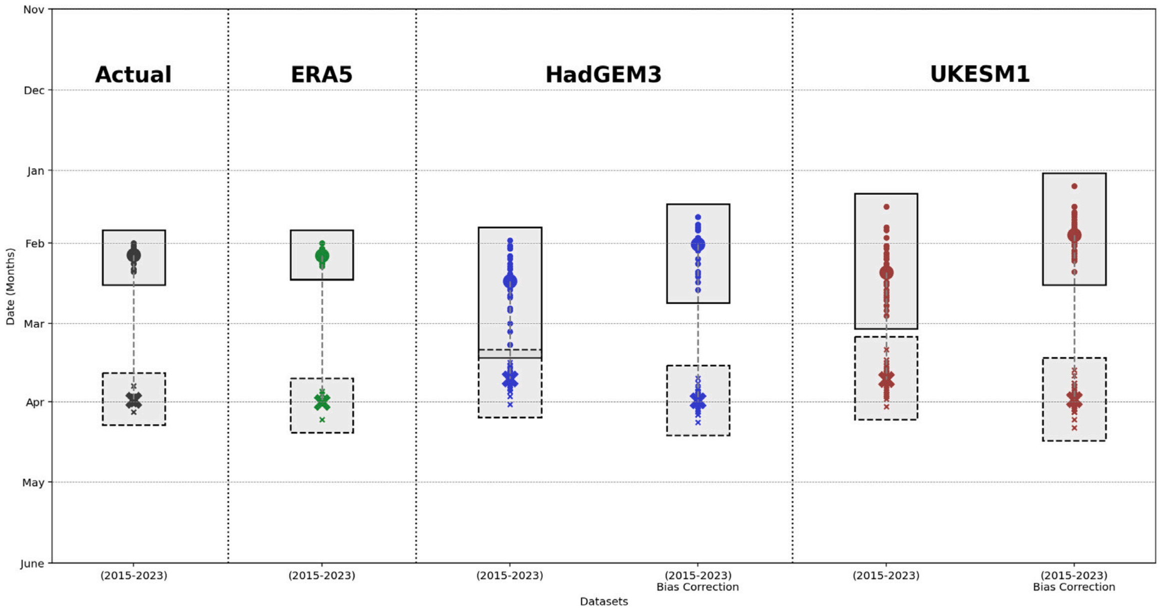

Fig. 3. The Northwest Territories Winter Roads, Ice Roads, and Ice Crossings – Historical Open and Close Dates, ERA5 Modelled Opening and Closing Dates, HadGEM3 Opening and Closing Dates, and UKESM1 Opening and Closing Dates. The data from each dataset spans years from 2015 to 2023, intended to provide validation for the Modelled ERA5 Opening and Closing Dates. The graph's y-axis displays the months, starting with November at the top and descending to June of the following year. The x-axis represents the different datasets, with the bias-corrected dataset shown beside the original dataset for HadGEM3 and UKESM1.

2.3. Testing model with different datasets

The HadGEM3 and UKESM1 models include variables for temperature and downward surface thermal radiation (downwelling longwave radiation) (Met Office Hadley Centre, 2022, 2025). When extracting data from HadGEM3, the coordinates for sub-region extraction were established with latitude bounds of 65.97°N to 62.27°N and longitude bounds of 114.2°W to 101.5°W. The chosen time interval for extraction was daily, encompassing all months of each year and all days of each month. Similarly, when extracting data from UKESM1, the coordinates for sub-region extraction were set to latitude bounds of 65.97°N to 62.27°N and longitude bounds of 114.2°W to 101.5°W. The selected time interval for extraction was daily, covering all months of each year and all days of each month.

Section 2.2 outlined the opening and closing dates by extracting the daily average temperature and surface thermal radiation from the HadGEM3 and UKESM1 models.

Upon determining the opening and closing dates from the extracted daily average temperature and downward surface thermal radiation datasets, a misalignment arises with the actual dates. To address this issue, a statistical technique known as bias correction is applied to the input data, including the extracted daily average temperature and downward surface thermal radiation. Bias correction identifies and rectifies biases within models, systems, or frameworks by systematically adjusting approximations and predicting biases due to various factors to promote an equitable outcome (Maraun, 2013).

A commonly used bias correction method in climate research for addressing biased model projections is quantile delta mapping (QDM) (Qian and Chang, 2021; Gergel et al., 2024; Cannon et al., 2015). As shown in Fig. 3, after bias correction, the HadGEM3 and UKESM1 models are much better aligned with the ERA5 dataset. Fig. 4, Quantile–Quantile (Q–Q) plots were employed to verify the effectiveness of QDM, revealing nearly perfect alignment between the ERA5 reference and the QDM-corrected HadGEM3 and UKESM1 ensembles across all quantiles. This demonstrates that distributional biases were effectively eliminated by QDM while maintaining the climate change signals. After determining the bias-corrected scale factor, it is applied to the future temperature and downward surface thermal radiation datasets from 2020 to 2100.

3. Results

This section evaluates and discusses the technical, economic, and environmental results. As Section 2 describes, we use the temperature and downward surface thermal radiation to determine the opening and closing dates. As described in Section 2.2 Datasets, the two datasets produce consistent results despite the differences in ensemble members.

3.1. Opening and closing dates

From Fig. 5, both the HadGEM3, shown in blue, and UKESM1, depicted in red, suggest that by 2060, using the minimum definition of 45 days, there will be little to no viable period for winter roads (Mullan et al., 2017). Similarly, both Figs. 5 and 6 show that as we approach the end of the 21st century, environmental conditions project that the temperature-based opening date is later than the downward surface thermal radiation-based closing date. This projection illustrates the impact of climate change on the TCWR, indicating that its viability is affected and suggesting the potential loss of operational viability of the TCWR.

3.2. Future viability of the TCWR

The HadGEM3 model is more optimistic than the UKESM1 model. It indicates that from 2020 to 2040, the average opening date falls on the 1st of February, while the average closing date is the 29th of March. During this period, 18 out of 20 years (90% of the time) featured viable winter roads. However, from 2040 to 2060, the average opening date shifts to the 9th of February, with the average closing date on the 25th of March, when 16 out of 20 years (80% of the time) still have a viable period. From 2060 to 2080, the average opening date becomes the 23rd of February, and the average closing date is the 21st of March, with 3 out of 20 years (15% of the time) achieving viability. From 2080 to 2100, the average opening date changes to the 14th of March, while the average closing date is the 17th of March. In this 20-year interval, there are not only no viable years, but some of the opening date ensembles are in April and later than the closing date, indicating the loss of operational viability of the TCWR. The HadGEM3

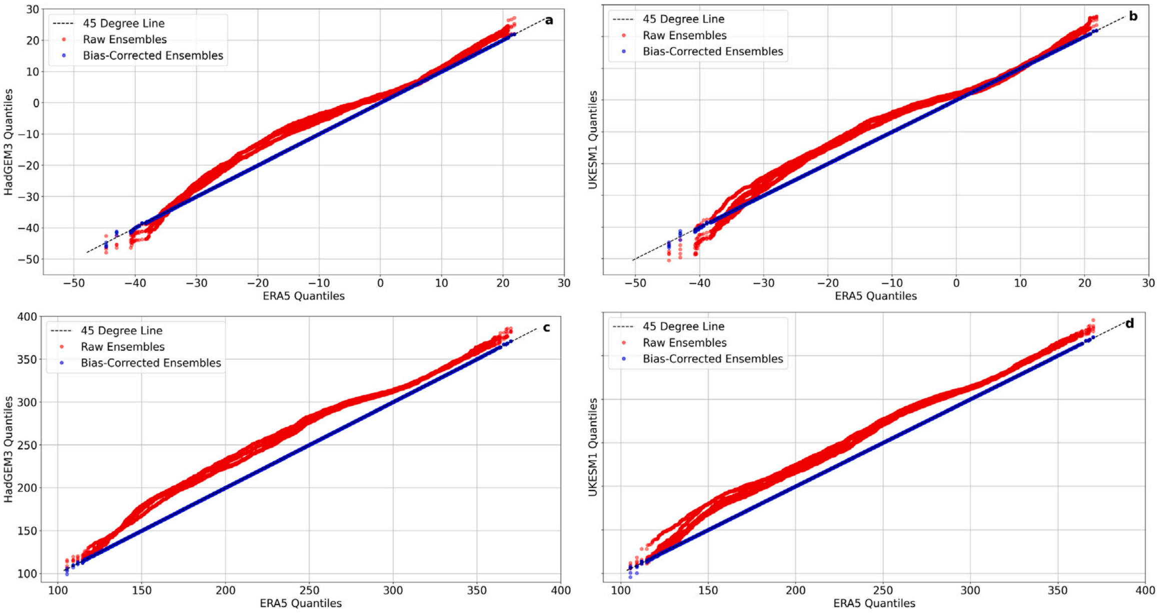

Fig. 4. Quantile–Quantile (Q–Q) plus graph for temperature and surface thermal radiation. (a) comparing HadGEM3 to ERA5 for the temperature ensembles from 2015 to 2023, where the red data points represent the raw data and the blue data points represent the bias-corrected data. (b) UKESM1 versus ERA5 for the temperature ensembles from 2015 to 2023, where the red data points represent the raw data and the blue data points represent the bias-corrected data points. (c) HadGEM3 versus ERA5 for the surface thermal radiation ensembles from 2015 to 2023, where the red data points represent the raw data and the blue data points represent the bias-corrected data. Likewise, (d) UKESM1 versus ERA5 for the surface thermal radiation ensembles from 2015 to 2023, where the red data points represent the raw data and the blue data points represent the bias-corrected data points.

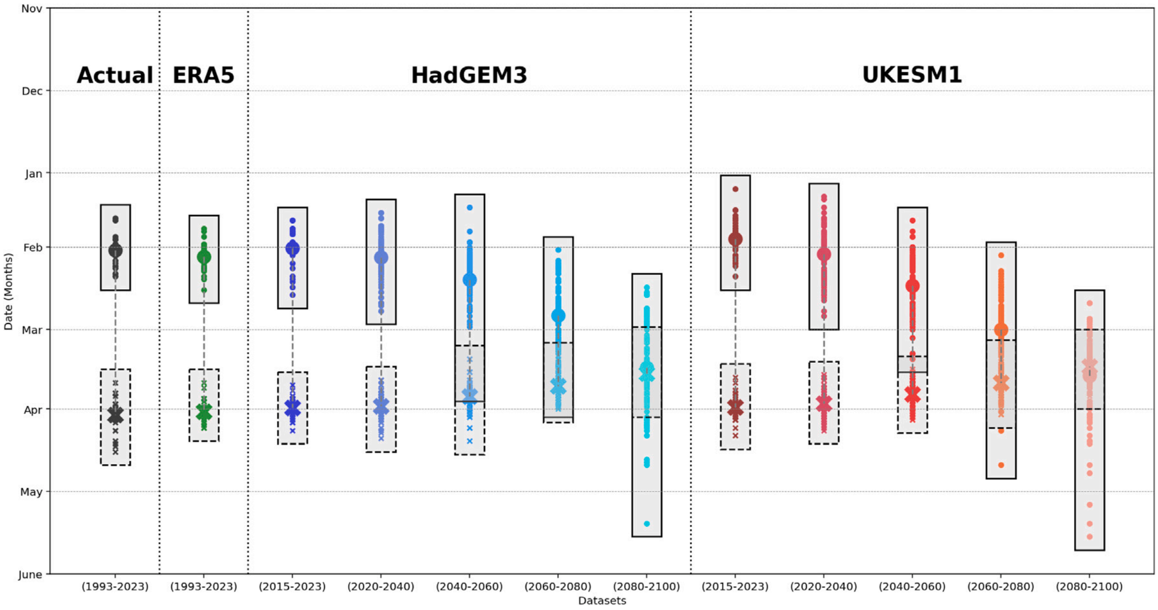

Fig. 5. Opening and closing dates of the Tibbitt to Contwoyto Winter Road from 1993 to 2100. The opening dates are indicated by a solid circle, with the average opening shown by a large solid circle. The closing dates are represented with Xs, with the average closing date denoted by a large X. The various datasets, starting from the left, include the Northwest Territories Winter Roads, Ice Roads, and Ice Crossings – Historical Open and Close Dates in black. The ERA5 Modelled Opening and Closing Dates are in green. The HadGEM3 dataset, plotted in blue, shows the opening and closing dates from 2015 to 2023. This same dataset is used to project future opening and closing dates at 20-year intervals from 2020 to 2100, with shades of blue becoming lighter. Similarly, the UKESM1 dataset, depicted in red, is first employed to plot the opening and closing dates from 2015 to 2023 and then to forecast future opening and closing dates at 20-year intervals from 2020 to 2100, with lighter shades of red.

model predicts that the opening date will be delayed by approximately 7 days in the first 20 years, increasing to 14 days in the subsequent 20 years and 21 days during the following 20 years, with the delay increasing by a factor of 2 every 20 years. Meanwhile, the closing date will consistently occur 4 days earlier every 20 years.

However, the UKESM1 model indicates that from 2020 to 2040, winter roads are viable only 65% of the time. It suggests that during this period, the average opening date is 31 January, while the average closing date is 28 March. Out of these 20 years, winter roads are viable in only 13 out of 20 (65% of the time). From 2040 to 2060, the average

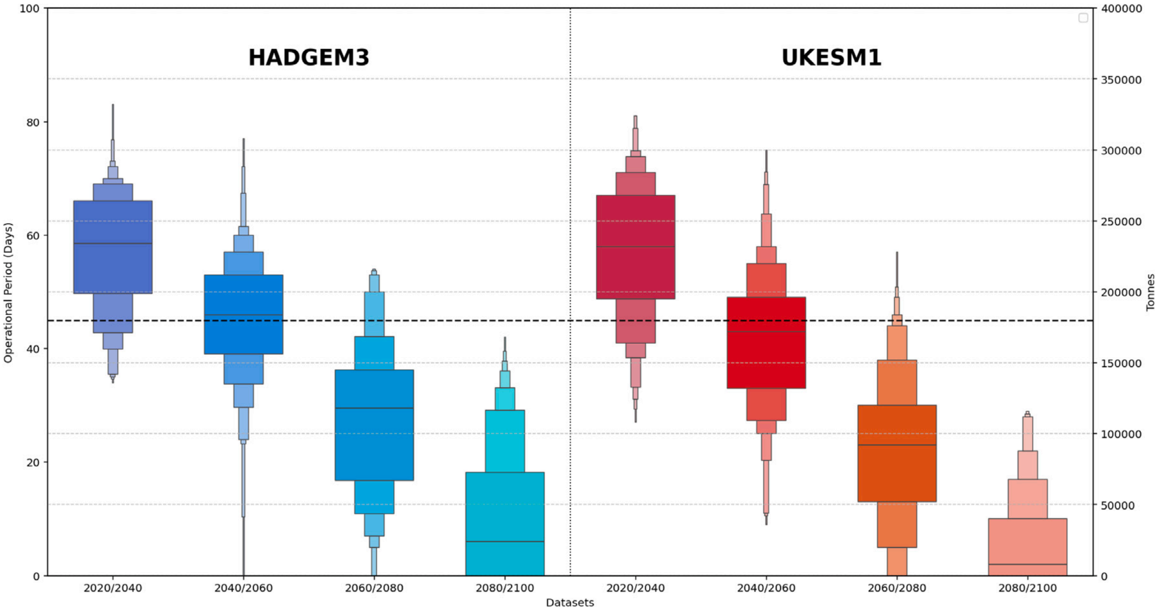

Fig. 6. HadGEM3 and UKESM1 models for the operational period from 2020 to 2100. The HadGEM3 dataset in blue plots projects future operational periods at 20-year intervals from 2020 to 2100, with shades of blue becoming lighter. Similarly, the UKESM1 dataset, depicted in red, forecasts future operational periods at 20-year intervals from 2020 to 2100, with lighter shades of red indicating the forecasted periods. The black dashed line in between represents the viable period of the TCWR, which is 45 days.

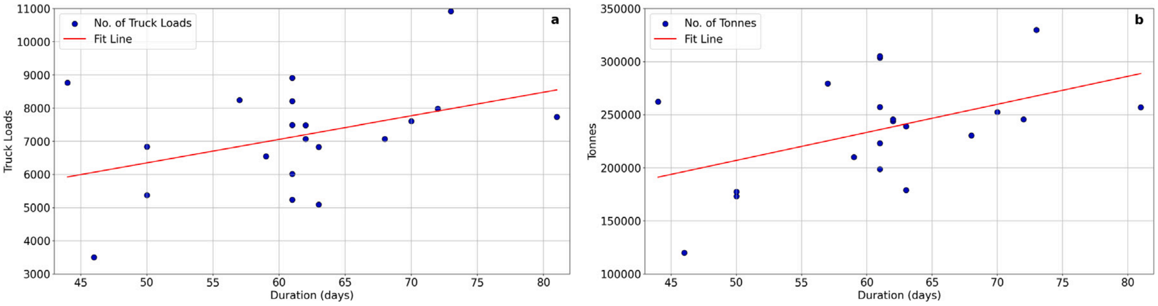

Fig. 7. Truck loads and tonnes transported VS. operational duration of the TCWR (2000–2020). (a) number of truckloads per year (blue dots). (b) number of tonnes transported per year (blue dots). The red line on each is the line of best fit.

opening date shifts to 11 February, with the average closing date being 24 March, and only 1 out of 20 years (5% of the time) having a viable period for the TCWR. From 2060 to 2080, the average opening date is 28 February, and the average closing date is 20 March, with no years in which the TCWR is viable. Finally, from 2080 to 2100, the average opening date is 17 March, and the average closing date is 14 March. During this 20-year interval, there are no viable years, with the average opening date being later than the average closing date, indicating the loss of operational viability of the TCWR. The UKESM1 model shows that the opening date will be delayed by approximately 11 days in the first 20 years, then by 17 days for each subsequent 20-year period. In contrast, the closing date will occur 4 days earlier every 20 years.

Based on Fig. 6, we can conclude that the primary factor contributing to the shortened operational period of the TCWR is the delay in opening dates, as for HadGEM3 model the delay will increase by a factor of 2 every 20 years, while for the UKESM1 model the delay is consistent of between 11 to 17 days every 20 years. In contrast, the closing date is less affected, as it is only brought forward by 4 days every 20 years (Wild et al., 2007).

4. Discussion

The TCWR is a crucial supply route for industries, especially diamond mines in Northern Canada. Based on Fig. 7, from 2001 to 2020, as the operational duration of the TCWR increases, the number of truckloads crossing also rises. Similarly, the tonnes transported across the TCWR also grow as the operational duration increases. Approximately, for every additional day of operations, 6800 more tonnes are being transported (Mullan et al., 2021).

For example, TCWR operations were suspended in 2005/2006 due to deteriorating ice conditions, resulting in only 50 days of operation and 6841 northbound truckloads transporting 177,674 tonnes of supplies to the region's industries.

The shortened operational period hindered the completion of the anticipated 9000 truckloads of deliveries, resulting in approximately 2000 undelivered loads. Additionally, due to the early closure, mining companies in the region turned to air transport, resulting in an estimated additional cost of $100 to $150 million CAD (Mullan et al., 2017).

Even though the TCWR operated for 73 days in 2007, facilitating 10,900 northbound truckloads that transported 330,002 tonnes of supplies to the region's industries—the highest volume recorded at that time—it failed to recover the losses from 2006, which resulted in the closure of the Jericho Diamond Mine in 2008 (Mullan et al., 2017).

Losses cannot be recovered after only one year of a shortened operational period. Current data shows that the TCWR will have little to no viability after 2060 and will be operationally non-viable by 2100.

This implies that the disappearance of the TCWR will lead to economic issues for the Northwest Territories, as utilising the TCWR for freight transport is significantly more economical than air transport. For some, the alternative is not feasible, as certain types of heavy machinery cannot be transported by air.

The importance of the TCWR must be recognised within the comprehensive transportation infrastructure of the Northwest Territories, where it cannot be replaced by a single mode of transport. Although air transport may be used when winter roads are inaccessible, it is significantly more expensive and cannot carry heavy-haul equipment (Government of Northwest Territories, 2015). Marine and barge transport, while more economical, is limited by geography, seasonal conditions, and water levels (Ruffilli, 2011). Consequently, winter roads remain a vital part of the regional freight network, ensuring reliable seasonal access for heavy supplies and industrial cargo that are difficult to move by other means. The expected reduction in the operational period of the TCWR shows it is not just a stand-alone route but also an essential component supporting the resilience of northern transportation systems.

The mining sector is a cornerstone of the Northwest Territories' economy, as diamond mines account for 78% of all mining-related production in the region and 26% of the total economic output of the Northwest Territories in 2010 (Government of Canada, 2012).

Consequently, climate change will lead to a loss of the TCWR, resulting in decreased mining activities, job losses, and reduced revenues for local communities and the territorial government (Perrin et al., 2015).

Mitigation methods to preserve the TCWR include reducing carbon emissions and lowering global temperatures to pre-industrial levels. Nevertheless, it is impossible to ignore the current rise in global temperatures, as most countries have not met the commitments of the Paris Agreement.

However, adaptation strategies for winter roads have been suggested. Given that climate change has shortened the operational period of the TCWR, one proposed solution is intensive artificial ice thickening, as this method can extend the safe operational window for the winter roads. Other suggestions have included alternative modes of transportation, such as tugboats and air transport.

Discussions are ongoing about the long-term transportation and infrastructure options for the Northwest Territories, including proposals for strategic routes associated with the Slave Geological Province Road (Tibbitt to Contwoyto Winter Road Joint Venture, 2025b). However, these initiatives should not be regarded merely as replacements for the TCWR, but rather as components that reflect broader objectives in transportation, economic growth, and resource development within the region. Recent evaluations by the government of the Northwest Territories have identified considerable mineral potential in the Slave Geological Province region, and the government maintains that strategic infrastructure investments will enhance accessibility, reduce transportation costs, and support future development initiatives (Aurora Geosciences Ltd., 2025). In this context, the TCWR is better understood as a case study of climate change affecting the operability of winter road systems, with the wider implications of these findings extending to transportation planning across the Northwest Territories and northern Canada.

Suggestions have been made for developing an all-season Slave Geological Province Road. This development aims to replace the seasonal TCWR, which costs over $20 million CAD and operates for approximately 67 days per year (Tibbitt to Contwoyto Winter Road Joint Venture, 2025b).

Although the Slave Geological Province Road is a $1 billion CAD investment, it is projected to yield a $39.2 billion CAD increase in gross output, a $20.2 billion CAD increase in GDP, and create 63,000 jobs in the Northwest Territories over the next 30 years. At the national level, the Canadian economy is expected to have a $61.5 billion CAD increase in gross output, a $31.5 billion CAD increase in GDP, and 157,000 jobs over the next three decades (Impact Economics, 2019).

Alternative methods include switching to summer transportation, as the Northwest Passage can transport mining supplies and equipment across the Arctic Ocean. Discussions suggest that marine shipping seasons are getting longer, offering potential for increased cargo movement through Arctic waters (Prowse et al., 2009). However, this proposal has its flaws, as the mines are not close to the ports, which causes a significant problem in transporting the equipment to the mines after it has been delivered to the ports.

5. Conclusion and future work

This paper develops a model to predict the future operational period of the TCWR in Northern Canada. It aims to identify the primary cause of the reduction in the TCWR operational period. The results obtained indicate that the viable period for winter roads will be limited between 2040 and 2060, suggesting economic uncertainty in the Northwest Territories. Furthermore, from 2060 to 2080, there will be little to no viable periods for the TCWR, as it would not be practical or economically feasible to sustain the TCWR. Lastly, from 2080 to 2100, if climate change continues, the TCWR will have no viable periods and become operationally non-viable, as the opening date will be later than the closing date.

Methods for assessing opening and closing dates have been introduced and discussed. This approach is not exclusive to the TCWR but can also be applied to other winter roads in Northern Canada.

Two distinct datasets (UKESM1 and HadGEM3) have been utilised to verify and determine future operational periods of the TCWR.

The results from the two datasets consistently indicate that the operational period of the TCWR will decrease. The primary cause of this reduction in the operational period is the delay in the opening date, while the closing date is not as significantly impacted over the 80 years.

With reduced operational periods leading to fewer truckloads of supplies, and equipment being transported on the TCWR. On average, with a reduced operational duration of 20 days, 50,000 tonnes less of supplies will be delivered. On average, each tonne is worth approximately $2500 CAD, indicating a loss of roughly $125 million CAD (Mullan et al., 2017).

As we approach the end of the 21st century and reach little to no viable opportunities for the TCWR by 2060, significant economic challenges will emerge for the region, as the Northwest Territories heavily rely on mining to sustain their economy and local employment (Deton' Cho Stantec and PwC, 2012).

The two datasets used to forecast future opening and closing dates, Had-GEM3 (four ensembles) and UKESM1 (five ensembles), have a sufficient number of ensembles. However, future improvements could include using datasets with more ensembles for more accurate predictions. The paper only explores scenarios where climate change remains uncorrected, assuming we continue our current trajectory of rising global temperatures. Further work might involve modelling scenarios where potential solutions are implemented to prevent shortening the operational period of winter roads.

In conclusion, the proposed FDD threshold of 1100 °C-days plus 42 days and the cumulative downward surface thermal radiation of 14,400 W/m^2 plus 8 days in the paper effectively predict the opening and closing dates for the TCWR. The results indicate that the operational period of the TCWR is decreasing, primarily due to delays in opening dates resulting from rising global temperatures. The viable period of the TCWR is likely to conclude reasonably before it disappears entirely, necessitating that those industries and the government find a suitable alternative route to replace the TCWR in Northern Canada. The methods developed in this paper for predicting the operational period of the TCWR can be applied to investigate other winter roads in Canada and their viable operational periods.

Although this study focuses on the TCWR, it uses this route as a case study to analyse how climate change will affect the operational viability of winter road systems more broadly. The threshold-based framework established herein can be extended to other winter roads across Canada to facilitate climate risk assessment and adaptation strategies, particularly during a period when infrastructure planning is intricately linked to long-term considerations concerning regional accessibility, strategic development, and future mining initiatives.

CRediT authorship contribution statement

Jerry Song: Writing – review & editing, Writing – original draft, Software, Methodology. **Sarah Sparrow:** Writing – review & editing, Supervision, Methodology, Conceptualization. **David Wallom:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The datasets used in this study are publicly available. ERA5 data are available from the Copernicus Climate Change Service (C3S) data store. HadGEM3 and UKESM1 data are available from the Centre for Environmental Data Analysis (CEDA). Historical winter road data are available from the Government of the Northwest Territories.

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