

# Analysis of Climatic Loading Parameters of Environment and Climate Change Canada for Climate-Resilient Flexible Pavement Design across Canada

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Paper prepared for the session {PV - Pavement Sustainability and the Vehicles of Tomorrow}  
2025 Transportation Association of Canada (TAC) Conference & Exhibition  
Québec City, Québec

## **Abstract**

Climate change has introduced significant challenges to the performance and durability of flexible pavements due to variations in temperature, precipitation, and freeze-thaw cycles. To address these challenges, it is essential to understand the influence of climate change on the key environmental parameters on pavement design. The Climate Adaptation and Asphalt Selection Tool (CAAST) was employed to capture the variations of climatic loadings on some of the key environmental parameters, while the Pavement Mechanistic-Empirical Design (PMED) tool was utilized to get the trends of the rest of the parameters for the four pavement design cycles of 25 years, ranging from 1995 to 2094. The analysis incorporates historical (1995–2019) and projected short-term (2020–2044), intermediate-term (2045–2069), and long-term (2070–2094) hourly climate data from Environment and Climate Change Canada (ECCC), which dynamically downscaled using the Canadian Regional Climate Model 4 (CanRCM4) for 17 different cities across Canada. Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) historical (1995-2020) climate data were also used to compare the ECCC's historical data to understand the trends of key climatic parameters. The downscaled climatic data were then fed into the CAAST and PMED to calculate critical environmental parameters such as Mean Annual Air Temperature (MAAT), Mean Annual Lowest Air Temperature (MALAT), Mean Annual Highest Air Temperature (MAHAT), Mean Annual Degree Days (MADD), Mean Annual Precipitation (MAP), freezing index, and average annual freeze-thaw cycles. It is found that the MAAT increases consistently across all cities, especially northern cities, which would experience a sharp increase, threatening permafrost stability. MALAT is also projected to rise, reducing risks of low-temperature cracking, particularly in southern regions, while MAHAT is expected to double in some areas, intensifying rutting. The MADD is found to rise significantly, indicating extended warm seasons; however, increasing MAP over the design cycle weaken pavement subgrade. The freezing index is declining, but freeze-thaw cycles in the Northern region tend to intensify the transitional zones, exacerbating pavement deterioration. These findings emphasize the importance of incorporating climate projections into road design for improved resilience.

**Keywords:** Climate Change, Environment and Climate Change Canada (ECCC), Pavement Mechanistic-Empirical Design (PMED), Climate Adaptation and Asphalt Selection Tool (CAAST), Climatic Parameters

## Introduction

Climate change is a pressing global issue, and understanding future climate conditions is crucial for planning and adaptation strategies. Climate change is primarily driven by human activities, particularly the burning of fossil fuels and land use changes such as deforestation and agriculture. These anthropogenic activities have significantly increased the concentration of greenhouse gases (GHGs) such as carbon dioxide, methane, nitrous oxide, and aerosols in the atmosphere, enhancing the natural greenhouse effect and leading to global warming<sup>1</sup>. Since the industrial revolution, the rate of GHGs emissions has accelerated, causing the earth's temperature to rise at an unprecedented rate over the past century<sup>2</sup>. Even though natural factors such as changes in solar radiation and volcanic eruptions sometimes influence the climate, their impact is insignificant compared to human-induced effects. The scientific consensus is clear that anthropogenic activities are crucially responsible for global warming since the mid-20th century<sup>3,4</sup>. As a result, the global average temperature has increased by about 1.1°C above pre-industrial levels, leading to profound impacts across nearly every sector of human civilization, including terrestrial ecosystems, marine and fisheries, agriculture, forestry, transportation, energy, and public health<sup>5</sup>.

The transportation sector, in particular, faces multifaceted and severe consequences, as it serves as a critical backbone for other industries such as tourism, construction, mining, and agriculture, all of which rely heavily on efficient transportation networks<sup>6</sup>. Among the climatic variables, roads and highways are very sensitive to temperature, precipitation, wind speed, solar radiation, relative humidity, freeze-thaw cycles, and groundwater level<sup>7</sup>. For instance, rising temperatures can reduce the service life of pavements by causing distresses such as longitudinal cracking, fatigue cracking, and rutting. It can also soften the asphalt, making it more susceptible to damage from traffic loading<sup>8</sup>. Changes in precipitation patterns and groundwater levels can weaken soil strength under pavements, leading to reduced service life. Increased groundwater levels in coastal regions can further exacerbate pavement deterioration<sup>9</sup>. The cumulative effect of freeze-thaw cycles causes significant damage to pavement by expanding and contracting water within cracks, leading to increased cracking, potholes, and structural weakening. This repetitive stress reduces pavement lifespan and requires costly repairs<sup>10</sup>.

Despite the growing body of research on climate change and pavement performance, several critical gaps remain. Most existing studies focus on coarse-resolution daily or monthly average climate conditions rather than using high-resolution, hourly climate projections necessary for capturing the extremes that directly impact pavement behavior<sup>11</sup>. Additionally, few studies combine historical observations with ensemble-based regional climate projections (e.g., CanRCM4) to comprehensively evaluate trends over multiple projected periods (short, intermediate, and long term). There is also limited integration of Pavement Mechanistic-Empirical Design (PMED) models with the Climate Adaptation and Asphalt Selection Tool (CAAST) to explicitly quantify how key climatic parameters evolve and what this evolution means for asphalt and aggregate selection, structural design, and maintenance scheduling of flexible pavement.

To address these gaps, this study employed a dual-tool approach: the CAAST was utilized to capture variations in temperature-related environmental parameters, i.e., Mean Annual Air Temperature (MAAT), Mean Annual Lowest Air Temperature (MALAT), Mean Annual Highest Air Temperature (MAHAT), Mean Annual Degree Days (MADD), while the PMED tool was used

to simulate the evolution of moisture and freeze-thaw related parameters, i.e., Mean Annual Precipitation (MAP), freezing index, and average annual freeze-thaw cycles. This integrated framework was applied across 17 Canadian cities, utilizing both Modern-Era Retrospective analysis for Research and Applications (MERRA-2) historical datasets and projected climate data from the Environment and Climate Change Canada (ECCC), dynamically downscaled using the Canadian Regional Climate Model 4 (CanRCM4). By systematically analyzing changes in the environmental parameters over four pavement design cycles (1995–2094), this research aims to provide a more accurate, region-specific understanding of future pavement vulnerabilities and offer guidance for climate-resilient pavement designs across Canada.

## **Goals and Objectives**

The goals of this study are as follows:

- Evaluate the impacts of climate change on key environmental parameters critical to flexible pavement analysis and design across different regions of Canada.
- Develop an integrated framework combining the asphalt selection tool (CAAST) and pavement design tool (PMED) for material selection and pavement design under future climate scenarios.

The main objectives of this study are as follows:

- Prepare hourly projected climate datasets spanning 1995–2094 using ECCC’s downscaled CanRCM4 model and historical (1995–2019) datasets from MERRA-2.
- Calculate key temperature and moisture-related environmental parameters using CAAST and PMED tools.
- Analyze temporal trends in key environmental parameters across 17 Canadian cities over four design periods, i.e., historical (1995–2019), short (2020–2044), intermediate (2045–2069), and long (2070–2094).
- Develop recommendations for incorporating projected climatic loadings into climate-resilient pavement design and management practices in Canada.

## **Methodology**

This study utilized continuous hourly climate data from 1995 to 2094, sourced from the ECCC<sup>12</sup> and generated through the CanRCM4<sup>13</sup> for the projected scenarios. The CAAST was employed to calculate key temperature-related environmental parameters, including MAAT, MALAT, MAHAT, and MADD, while PMED simulations were conducted in parallel to derive moisture and freeze-thaw related parameters such as MAP, freezing index, number of wet days, and average annual freeze-thaw cycles. Seventeen cities were strategically selected across Canada to represent a range of climatic zones, including Atlantic Canada, Central, Prairies, Western Canada, and Northern Canada. Climate trends were analyzed across four pavement design cycles: historical (1995–2019), short (2020–2044), intermediate (2045–2069), and long-term (2070–2094). MERRA-2 historical datasets were incorporated to compare and validate the ECCC’s historical data and better understand the baseline climatic trends. The integration of CAAST and PMED enabled a comprehensive evaluation of the impact of changing temperature, precipitation, and freeze-thaw cycles on flexible pavement performance.

## **Climate Data Collection and Preparation**

This study utilized high-resolution climate datasets to analyze the impact of climate change on pavement-relevant environmental parameters across Canada. The historical MERRA-2 climatic dataset from the National Aeronautics and Space Administration (NASA) and projected datasets provided by the ECCC were used. The historical MERRA-2 data were indirectly retrieved through the LTPPBind software of the Long-Term Pavement Performance (LTPP) website <sup>14</sup>. The projected datasets were generated by ECCC’s Canadian Centre for Climate Modelling and Analysis (CCCma) using the CanRCM4 model, and distributed through the Computer Research Institute of Montreal (CRIM), Ouranos, the Pacific Climate Impacts Consortium (PCIC), the Prairie Climate Center (PCC), and HabitatSeven across Canada from 1950 to 2100 <sup>13</sup>. The projected climatic loading files are derived from a large 50-member ensemble of high-resolution (0.44° ~50 km) North American simulations conducted by ECCC and sampled hourly. These datasets are based on regional simulations with CanRCM4, driven at the boundaries by global CanESM2 simulations. Under the highest emission scenario (Representative Concentration Pathway, RCP 8.5), the mean temperature in Canada is projected to increase by approximately 6°C by the late 21<sup>st</sup> century, according to outputs developed by the CCCma <sup>15</sup>. In this study, it was assumed that the road section was built in 1995 for a design life of 25 years. More details of cycle numbers and the projected design period are shown in Table 1.

Table 1: Projected design period

<b>Cycles number</b>	<b>Term</b>	<b>Design life (25 years)</b>
1	Historical	1995 – 2019
2	Short	2020 – 2044
3	Intermediate	2045 – 2069
4	Long	2070 – 2094

## **Selection of Study Locations**

The study focused on 17 cities across Canada, as shown in Figure 1, selected to ensure geographical diversity and represent a broad spectrum of climatic conditions affecting road infrastructure. These include:

- Atlantic Canada: St. John’s, Halifax, Charlottetown, and Fredericton
- Central Canada: Québec City, Ottawa, Toronto, Windsor, and Montreal
- Prairies: Winnipeg, Regina, Saskatoon, Edmonton, and Calgary
- Western Canada: Vancouver
- Northern Canada: Whitehorse, Yellowknife



## **Key Environmental Parameters Using PMED**

The Pavement Mechanistic-Empirical Design (PMED) tool was employed to evaluate the impact of climate-sensitive environmental parameters on flexible pavement performance over time. PMED integrates climate data through its Enhanced Integrated Climatic Model (EICM), which simulates heat and moisture transfer processes within the pavement structure. This study inputted continuous hourly climate data from MERRA-2 and ECCC for the four pavement design cycles mentioned in Table 1 to capture variations in critical parameters as follows:

- Mean Annual Precipitation (MAP)
- Freezing Index
- Average Annual Freeze-Thaw Cycles

These variables are essential in predicting pavement distresses such as rutting, thermal cracking, and moisture-induced damage. The freezing index and freeze-thaw cycles were particularly emphasized due to their relevance in Canadian regions susceptible to seasonal temperature fluctuations. The EICM's sub-models, such as Infiltration and Drainage (ID) model, Frost Heave and Thaw Settlement model, and Climatic-Materials Structural (CMS) model <sup>8</sup>, process these inputs to compute layer-specific temperature and moisture profiles, enabling accurate performance forecasts under both historical and projected climatic conditions.

## **Results and Discussion**

In this study, several environmental parameters that are very sensitive to flexible pavement performance were analyzed using comprehensive tools such as CAAST and PMED for 17 Canadian cities, assuming pavement design life of 25 years and four design cycles ranging from 1995 to 2094.

### **Environmental Parameters Analyzed Using CAAST**

Two different data files used in this study were MERRA-2 and ECCC for the historical period of 1995 to 2019 for the cities of Ottawa, Halifax, Vancouver, Edmonton, Calgary, Saskatoon, Regina, Winnipeg, Toronto, Montreal, Québec, Charlottetown, Fredericton, St. John's, Yellowknife, Whitehorse, and Windsor. The environmental loading parameters for MERRA-2 and ECCC were calculated using LTPPBIND and CAAST software, respectively, and then compared. The comparison results in terms of MALAT, MAHAT, and MADD are shown in Figure 2, Figure 3, and Figure 4, respectively.

The results reveal that MALAT (Figure 2) values derived from MERRA-2 data are consistently lower than those obtained from ECCC data across all cities. This discrepancy is particularly pronounced in Atlantic Canada, such as St. John's, Charlottetown, and Fredericton, while less pronounced in Central Canada, such as Québec, Windsor, and Ottawa. Overall, MALAT shows a generally warmer trend in the ECCC data, exceeding the MERRA-2 values by about 10% to 82%. The consistently colder trend of MALAT values from MERRA-2 suggests that the choice of climate data source can significantly influence the estimation of environmental loading parameters, which are critical for pavement design and asphalt selection.

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The MAHAT of seven consecutive days (Figure 3) shows a higher trend with a 7% to 30% increase in ECCC data compared to MERRA-2. This difference is particularly notable in cities such as Toronto, Winnipeg, and Windsor, where the ECCC-based MAHAT exceeds the MERRA-2 values by about 20%. The observed trend suggests that ECCC station data tend to capture higher extreme temperature events compared to the gridded reanalysis data from MERRA-2. These discrepancies underscore the significant impact that the choice of climate data source can have on estimating high-temperature environmental loading parameters, which are critical for pavement design and performance assessment, especially in regions prone to heat extremes. The MADD illustrated in Figure 4 shows an increase using ECCC data compared to MERRA-2 about 59%, 78%, 75%, 38%, 40%, and 50% in Vancouver, Toronto, Halifax, Yellowknife, Winnipeg, and Windsor, respectively. A range of about 14% to 33% increases can be noticed for the rest of the cities, such as Ottawa, Edmonton, Calgary, Saskatoon, Regina, Yellowknife, Montreal, Québec, Charlottetown, and Fredericton. All ECCC's data trends are in good agreement with general consciences that the temperature trend in Canada has increased more than the global rate<sup>15</sup> and adopting ECCC data and using it in CAAST software is a more accurate choice.

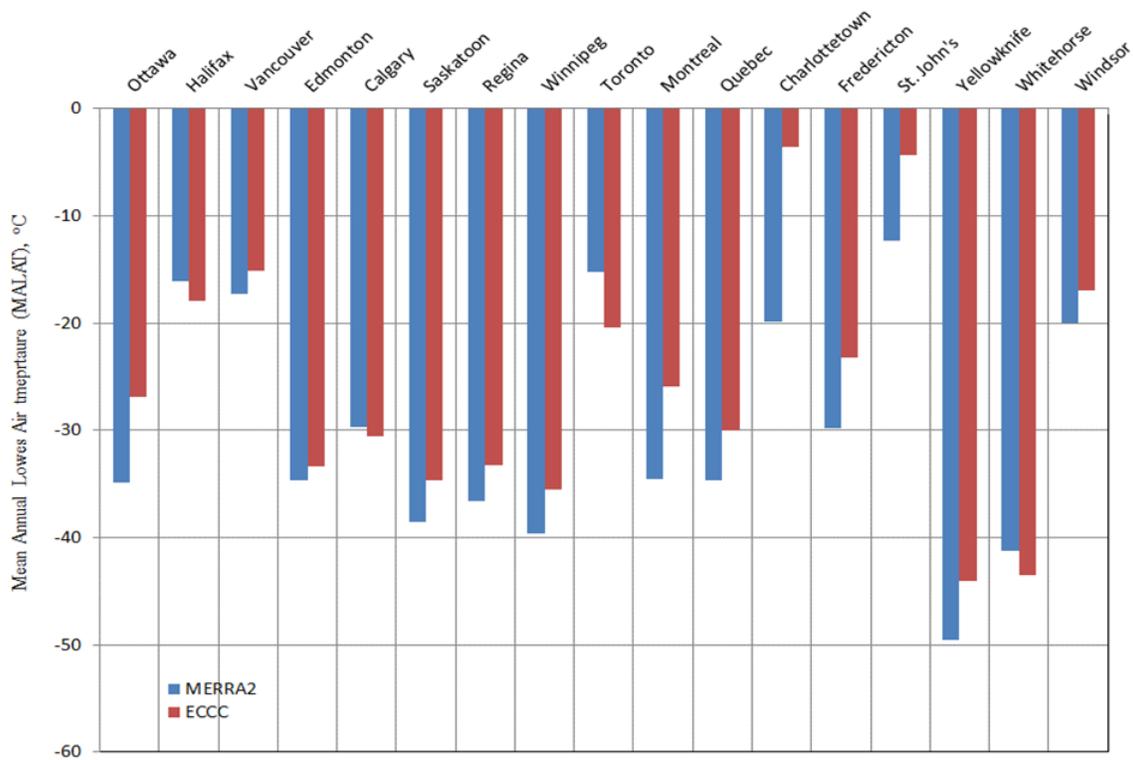


Figure 2: Comparison of mean annual lowest air temperature (MALAT) for MERRA-2 and ECCC historical climate data

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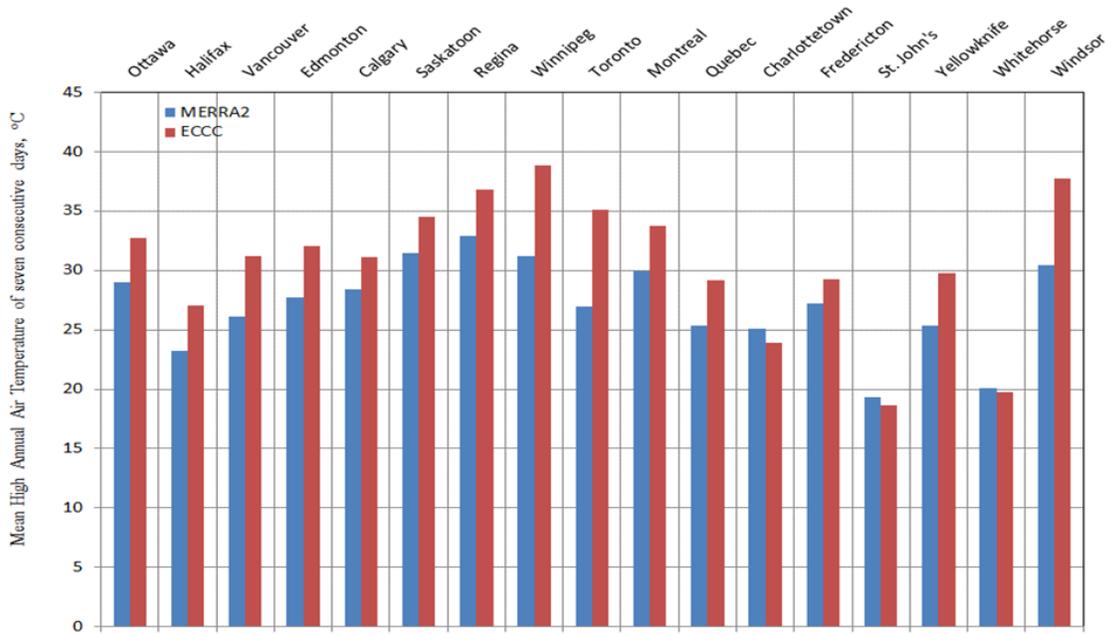


Figure 3: Comparison of mean annual high air temperature (MAHAT) of seven consecutive days between MERRA-2 and ECCC historical climate data

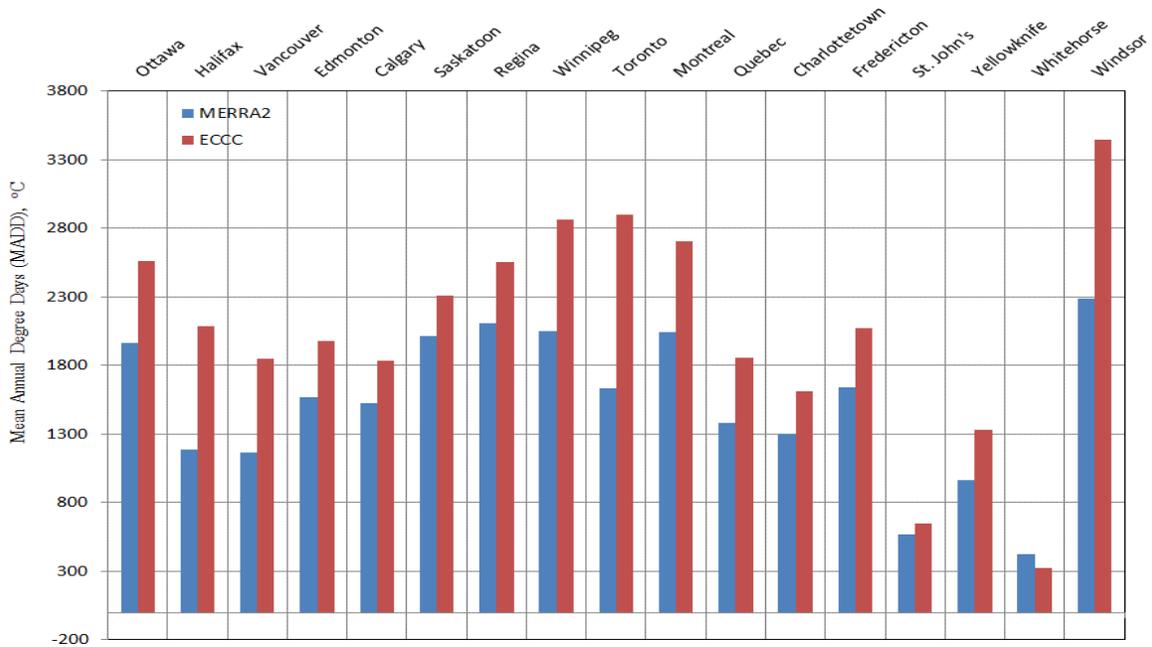


Figure 4: Comparison of mean annual degree days (MADD) between MERRA-2 and ECCC historical climate data file

ECCC’s projected temperature data for the cycles described in Table 1 were analyzed using CAAST software to determine the yearly air temperature parameters such as MAAT, MALAT, and MAHAT, and MADD over 10°C for selected cities mentioned earlier across Canada.

***Mean Annual Air Temperature (MAAT)***

Projected climatic data from the ECCC’s CanRCM4 model for road design cycles, shown in Table 1, were used to summarize and describe the average climatic conditions of particular cities in terms of MAAT. Figure 5 shows a general trend of temperature increase in all selected Canadian cities for this study. Among the southern cities, Windsor is expected to experience the highest MAAT, about 17°C by the end of the 21<sup>st</sup> century, which is about a 42% rise from the historical baseline (Figure 6). In contrast, northern cities like Whitehorse and Yellowknife, while starting with much lower baseline temperatures, also show substantial warming, with MAAT rising from well below zero to above freezing by the latter half of the century. For instance, in Yellowknife, the MAAT will increase to about 4.2°C (Figure 5) by 2094, which is about a 321% rise compared to historical trends (Figure 6). Notably, the lines for all cities exhibit a steady upward trajectory, highlighting the pervasive impact of climate change on regional temperature regimes. Changes in the projected range of temperatures, including seasonal changes in MAAT, can also impact highway systems. The increase in MAAT ranges will likely benefit highways in some ways while increasing risks in others. Further analysis of Figure 5 shows that the temperature in the North of Canada, represented by Yellowknife and Whitehorse, is climbing very fast and is projected to accelerate permafrost degradation, particularly around mid (≈2050) and late (≈2075) century, respectively.

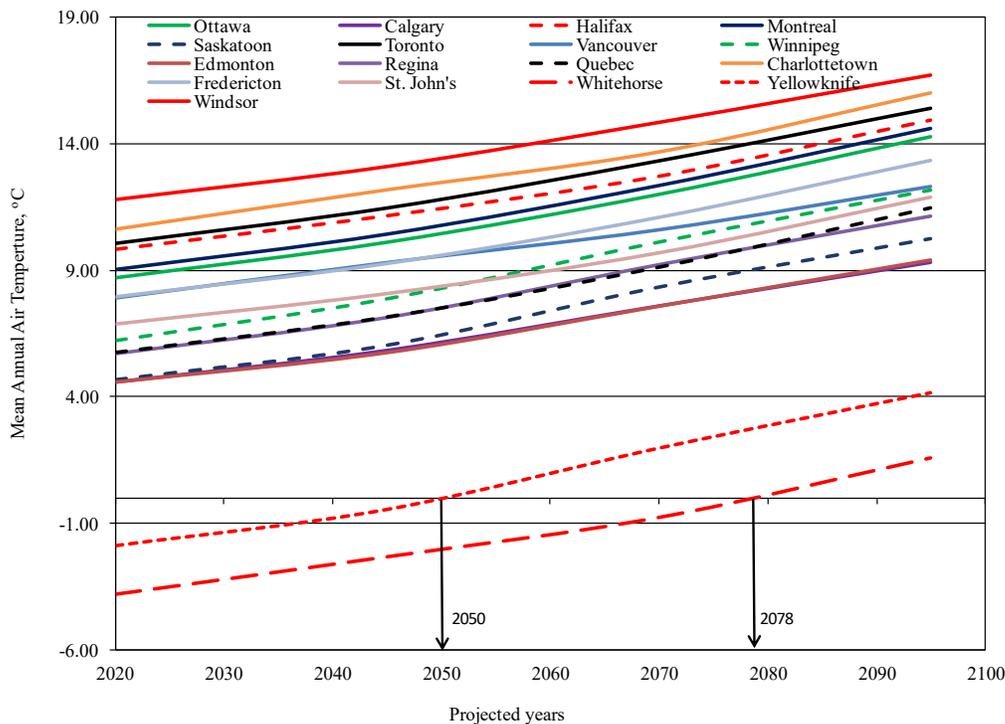


Figure 5: Mean annual air temperature (MAAT) using CAAST for projected climate data

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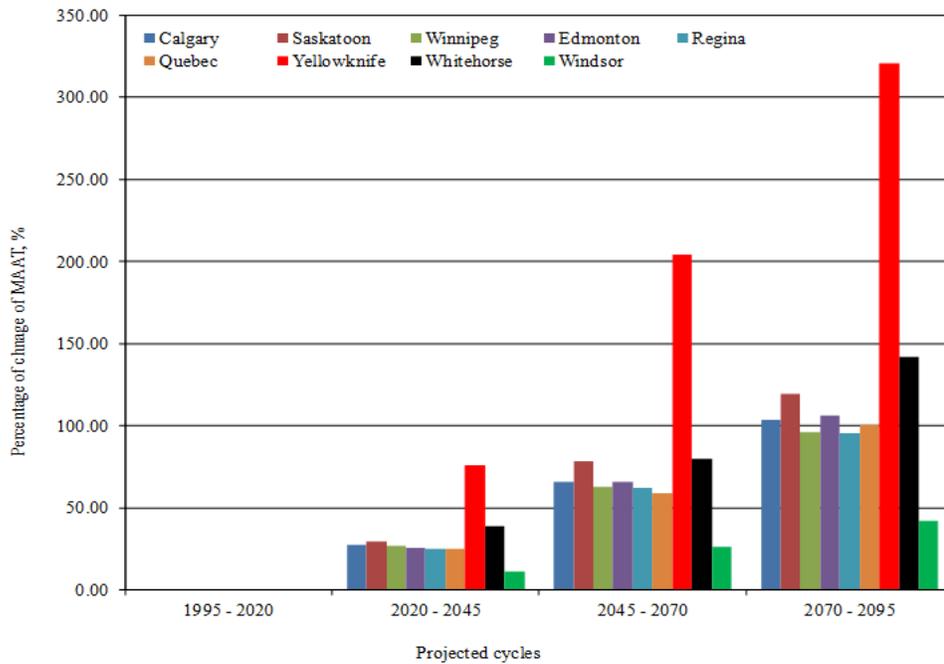


Figure 6: Percentage of change of MAAT over the projected cycles

***Mean Annual Lowest Air Temperature (MALAT)***

The hourly projected temperature data were analyzed using CAAST to determine the Mean Annual Lowest Air Temperature, as illustrated in Figure 7. It shows that the coldest annual temperatures are expected to become progressively warmer over time, reflecting a significant reduction in extreme cold events. Notably, northern cities such as Whitehorse and Yellowknife, which currently experience the lowest MALAT values, are projected to see the most pronounced increases, with their MALAT curves rising sharply. Also, Charlottetown and St. John’s will experience temperatures above zero in around mid ( $\approx 2059$ ) and third quarter ( $\approx 2071$ ) of 21<sup>st</sup> century, respectively. Increasing MALAT over the projected years will be beneficial to road construction by reducing the lowest threshold of asphalt performance grade.

Figure 8 illustrates the percentage change in MALAT for selected cities over successive projected cycles: 1995–2019 (baseline), 2020–2044 (short), 2045–2069 (intermediate), and 2070–2094 (long). The bars for each city show increasingly negative values over time, indicating a substantial warming trend in the annual minimum temperatures. However, it is noticed that the maximum percentage of increase in MALAT is about 216% and 147% in Charlottetown and St. John’s cities, respectively. The Northern part of Canada shows changes averaging 20% to 50% from the historical baseline.

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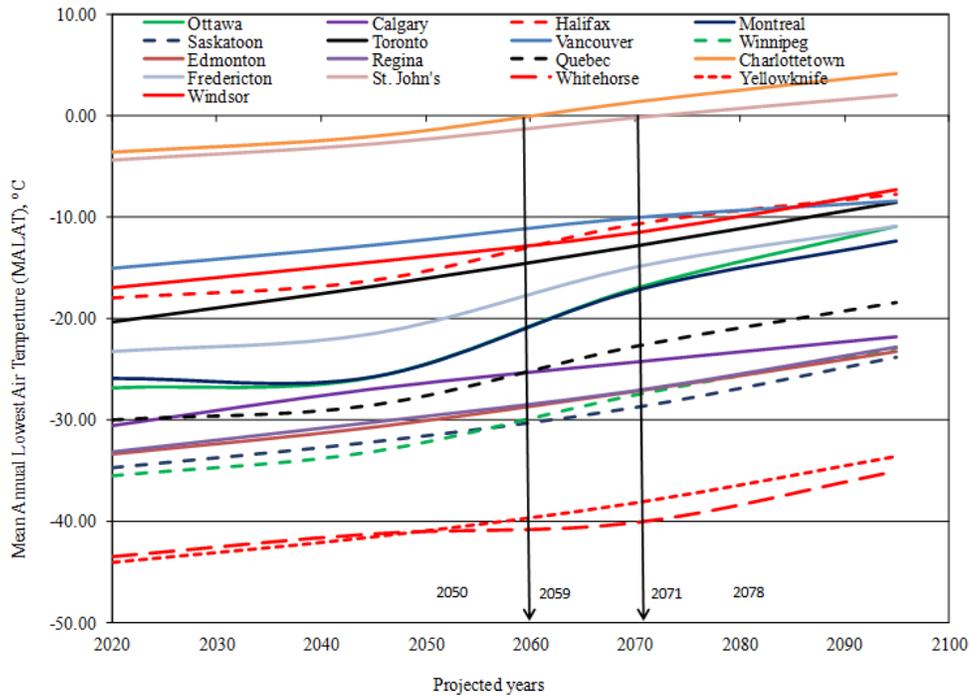


Figure 7: Mean annual lowest air temperature (MALAT) using CAAST for projected climate data

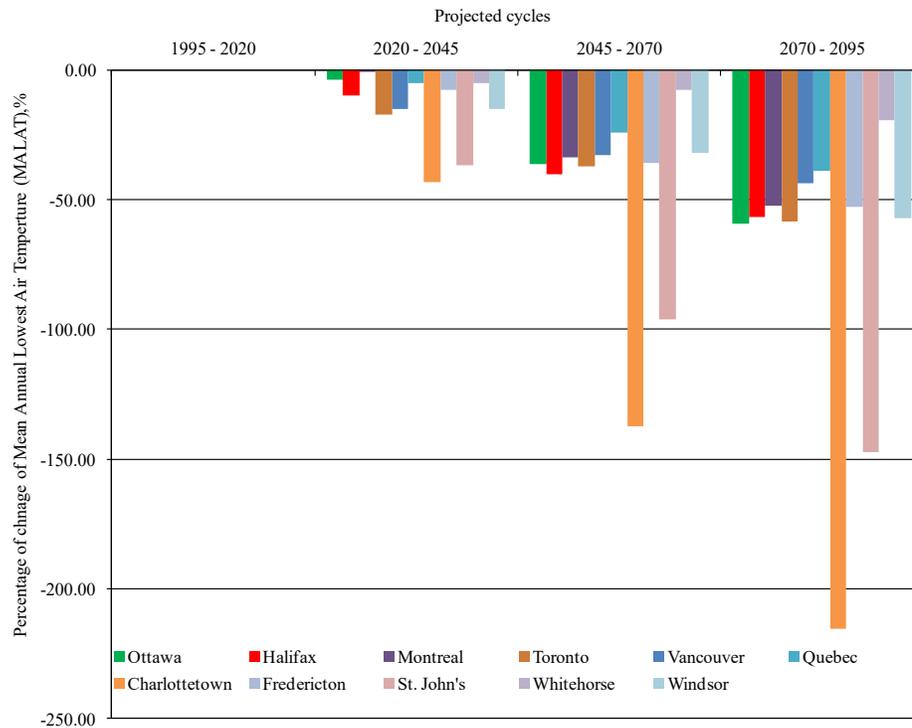


Figure 8: Percentage of change of MALAT over the projected cycles

***Mean Annual Highest Air Temperature (MAHAT)***

The hourly projected temperature data were analyzed using CAAST to determine the MAHAT, as illustrated in Figure 9. It indicates that the MAHAT has increased gradually over the centuries for all cities, which is directly aligned with the effect of climate change and global warming. This trend is more noticeable in one of the prairie cities, i.e., Winnipeg, which experienced the highest MAHAT of about 42°C at the beginning of the projected cycle and reached about 48°C by the end of this century. Interestingly, it is noticed that the MAHAT constantly increases from one projected cycle to the previous one by almost double, for instance, 5%, 10%, and 20% increase in the case of projected cycle 2, 3, and 4, respectively, with respect to projected cycle 1 (historical term), as shown in Figure 10. This finding is alarming; thus, it is crucial to change the temperature and performance grade binder selection procedure during the road design life.

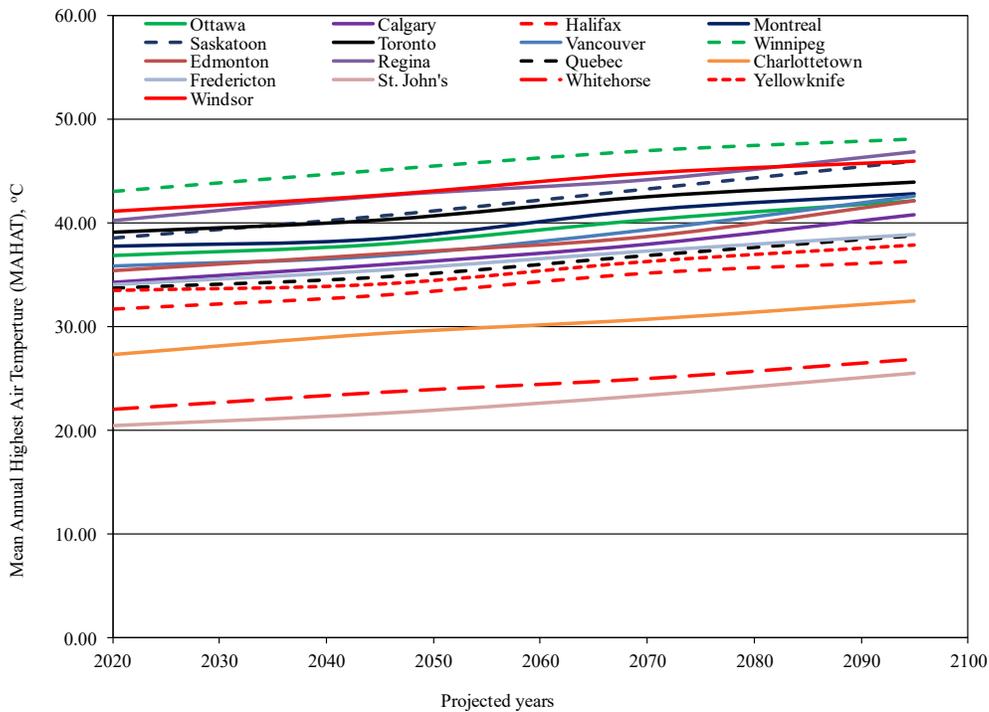


Figure 9: Mean annual highest air temperature (MAHAT) using CAAST for projected climate data

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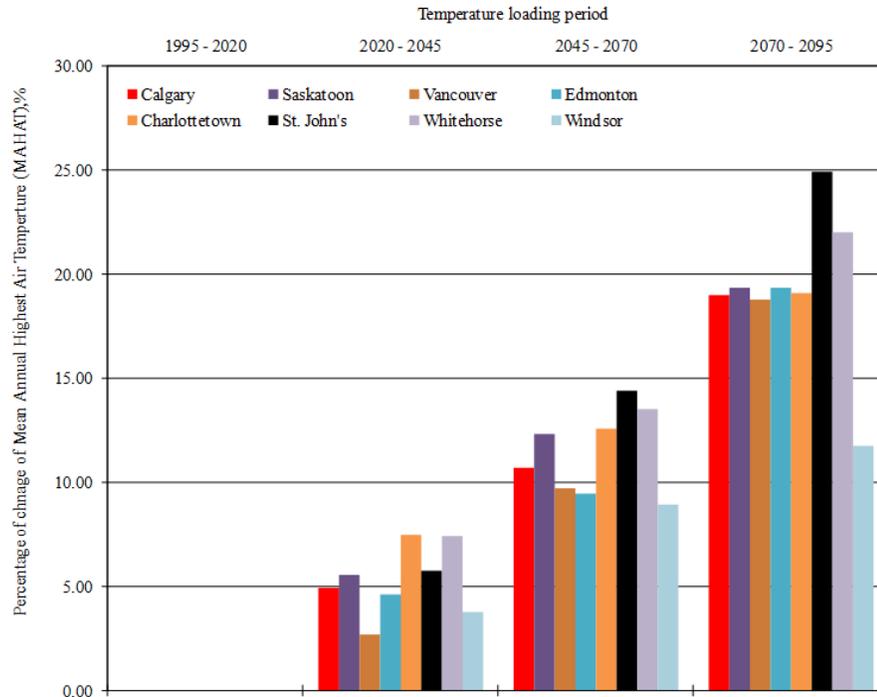


Figure 10: Percentage of change of MAHAT over the projected cycles

***Mean Annual Degree Days (MADD)***

The newest change in the LTPPBind was in September 2018, which includes switching to Degree Days over 10°C from the months of April to September of each year, instead of seven consecutive days of high air temperature. In CAAST, the calculation is not limited to the range between April and September, as it is in LTPPBind, but includes the whole year. The MADD over 10°C is used to calculate the Mean Annual High Pavement Temperature (MAHPT). The MAHPT is selected based on a rutting damage model<sup>16</sup> and extreme weather events represented by reliability factors. The general trend shown in Figure 11 indicates that the MADD increases gradually over the projected years, and it will be the highest in the city of Windsor (4900°C d-d) and lowest in the city of Whitehorse (900°C d-d) by the year 2094.

Further analysis illustrated in Figure 12 indicates that most of the cities show an increase of MADD of 10%, 30%, and 60% in projected cycles 2, 3, and 4, respectively, with respect to projected cycle 1. City of St. John’s shows an increase of about 31%, 75%, and 153%, the city of Charlottetown shows an increase of about 20%, 43%, and 83%, and the city of Whitehorse shows an increase of 40%, 81%, and 162% in the projected cycles 2, 3, and 4, respectively.

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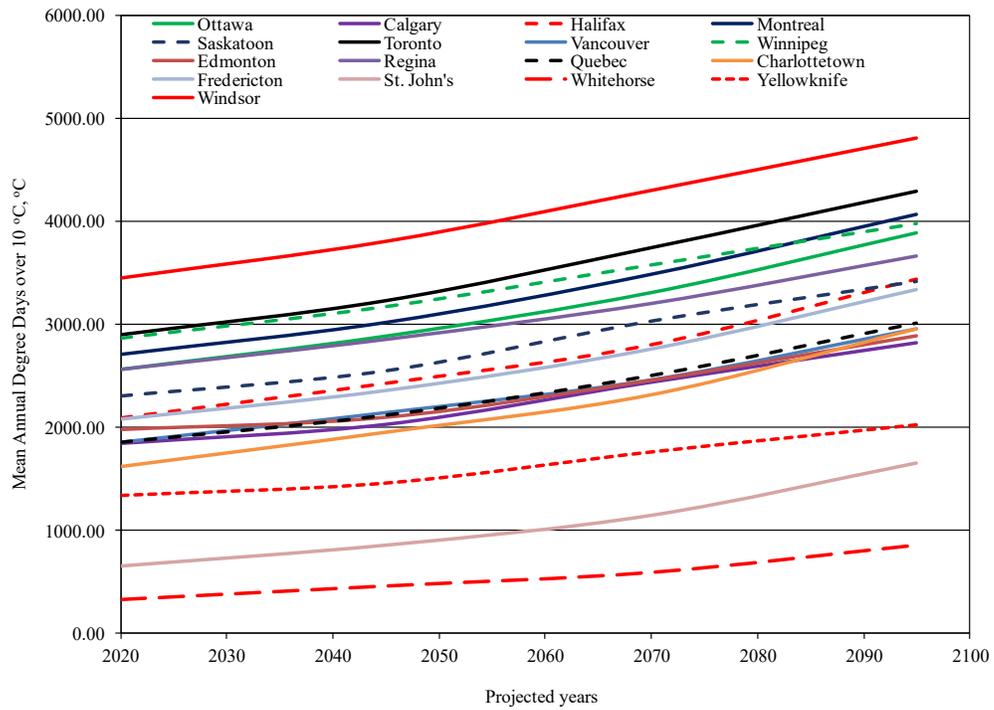


Figure 11: Mean annual degree days (MADD) using CAAST for projected climate data

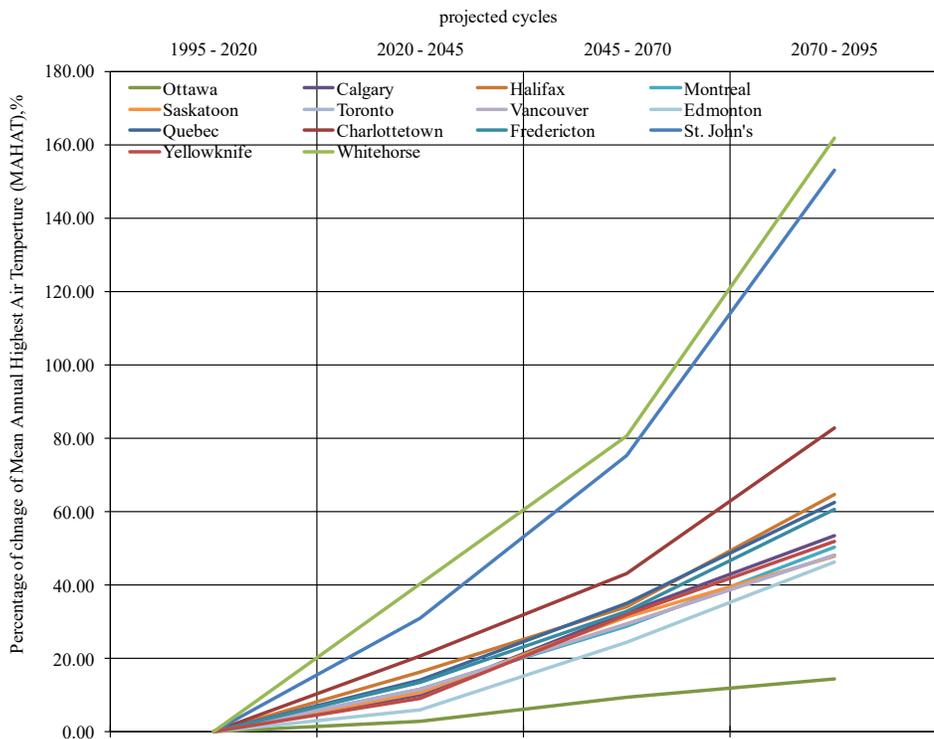


Figure 12: Percentage of change of MADD over the projected cycles

**Environmental Parameters Analyzed Using PMED**

Projected climatic data prepared by Environment and Climate Change Canada for road design cycles, as shown in Table 1, were incorporated into PMED to summarize and describe the key moisture-related environmental loading parameters for selected cities across Canada.

***Mean Annual Precipitation (MAP)***

Figure 13 illustrates the projected changes in MAP for nine major Canadian cities-Ottawa, Halifax, Toronto, Vancouver, Saskatoon, Winnipeg, Calgary, Montreal, Whitehorse, and Windsor across four future climatic loading periods. The graph shows that Vancouver consistently receives the highest mean annual precipitation among the cities, with values starting near 1800 mm and rising to over 2000 mm by the end of the projection period. Halifax also exhibits high precipitation levels, fluctuating around 1500 mm and showing a modest increase mid-century before stabilizing. Montreal, Ottawa, Toronto, and Windsor experience moderate precipitation ranging from 900 to 1200 mm, with slight upward trends over time. The cities of Saskatoon, Winnipeg, Calgary, and Whitehorse have the lowest mean annual precipitation, all starting below 600 mm. However, these cities show a gradual increase in precipitation over the projection periods, with Whitehorse and Calgary in particular displaying a more pronounced upward trend. Overall, Figure 13 highlights a general pattern of increasing mean annual precipitation across all cities, although the magnitude and rate of increase vary by location.

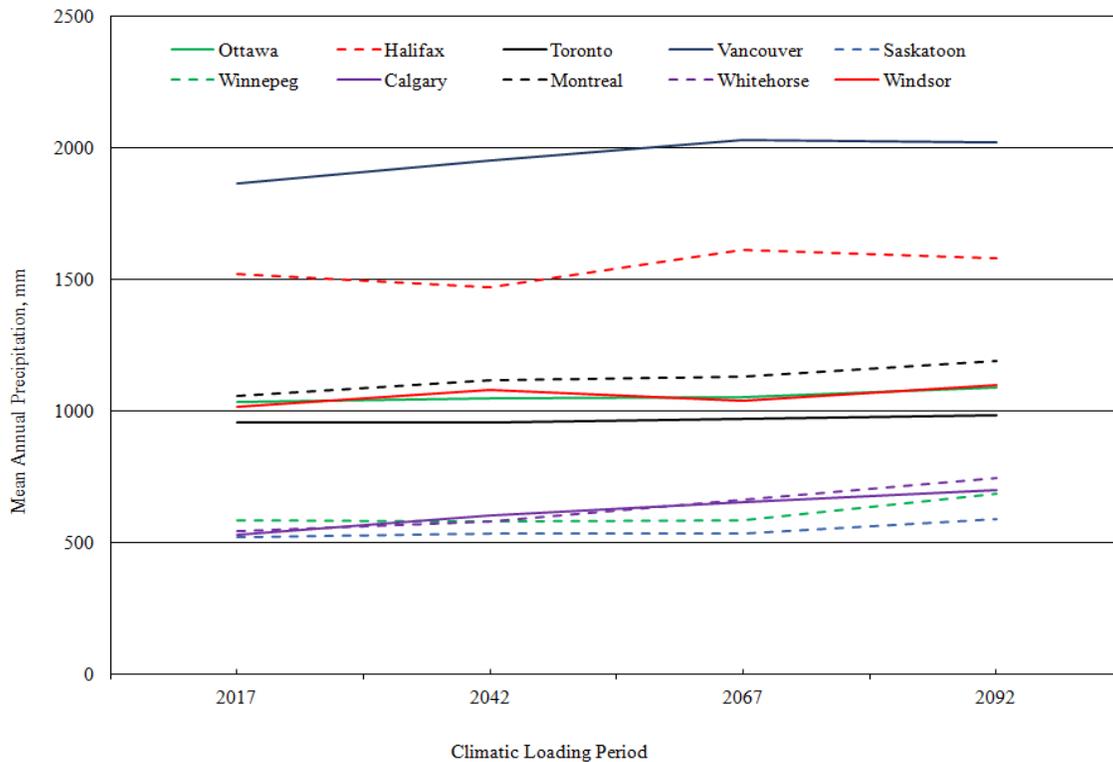


Figure 13: Mean annual precipitation (MAP) using PMED for projected climate data

***Freezing Index and Freeze-Thaw Cycles***

Using PMED to analyze the projected climate data, it was found that increased temperature consequently resulted in less frost. This finding is essential in terms of flexible pavement performance. Figure 14 indicates that climate warming is causing a general decrease in the freezing index, leading to a reduction of about 89% and 47% in the freezing index of Windsor and Whitehorse, respectively.

Soil in cold regions may undergo several freeze and thaw cycles each year, as shown in Figure 15. It is found in this study that when MAAT is above and below 2°C (Figure 5), it decreases and increases the freeze and thaw cycles, respectively, so the majority of the road infrastructure in the northern part of Canada will be impacted by climate change due to the increase in freeze and thaw action. The resilient modulus as a measure of unbound material stiffness increases tremendously when frozen during winter, then drops below normal stiffness right after the thawing season and slowly recovers to normal values during the late spring and summer. These variations in unbound material stiffness are captured in the new PMED using EICM’s sub-models for freeze-thaw adjustment factors using site-specific climate input files <sup>17</sup>.

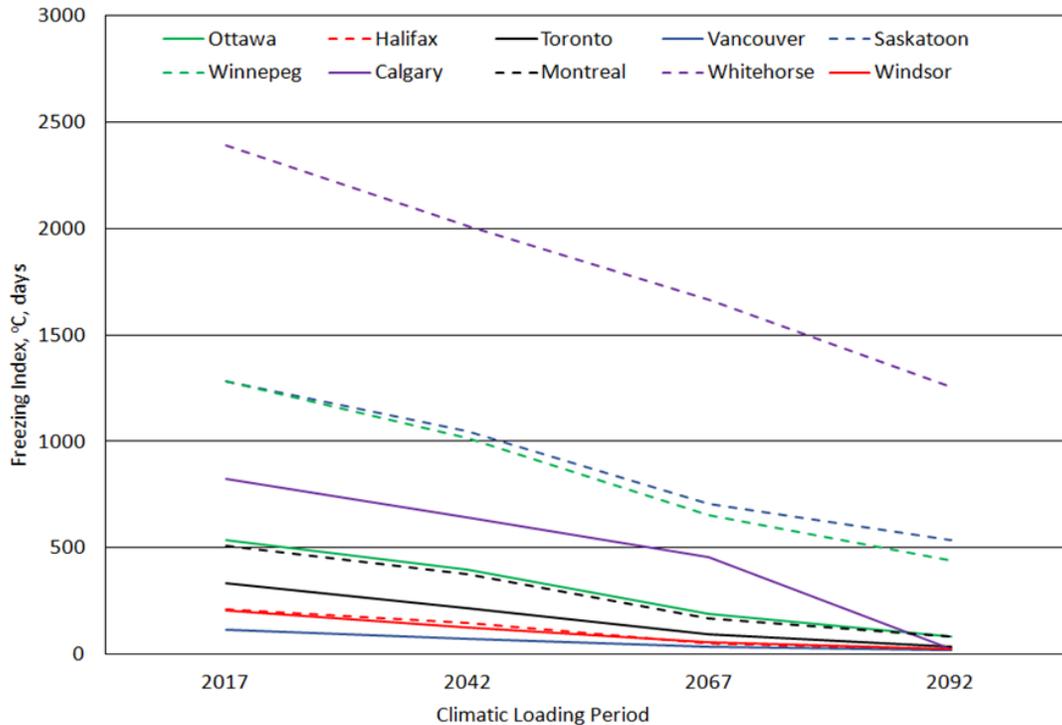


Figure 14: Freezing Index using PMED for projected climate data

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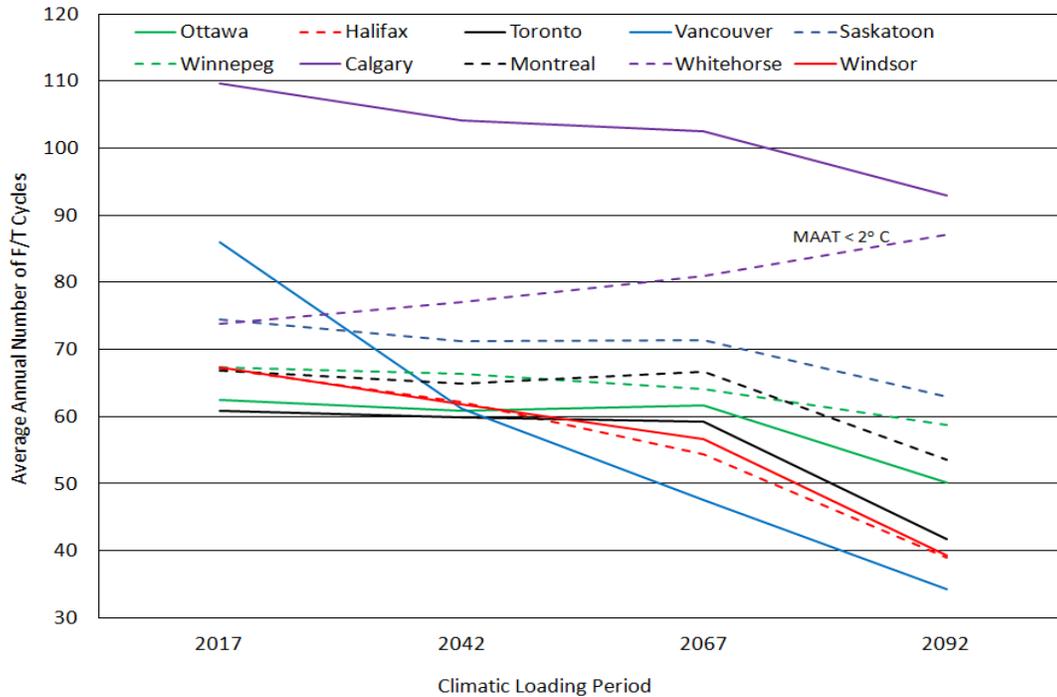


Figure 15: Average annual number of freeze and thaw cycles using PMED for projected climate data

## Conclusion

The analysis conducted in this study demonstrates the substantial impact of projected climate change on key environmental parameters that influence asphalt selection and flexible pavement performance across Canada. Using a dual-tool framework involving CAAST and PMED, the study reveals consistent increases in average air temperature, degree days, precipitation, and intensified freeze-thaw dynamics in specific regions. The comparison between MERRA-2 and ECCC’s historical datasets and trends on ECCC’s projected datasets highlights the significance of choosing appropriate climate data sources and time periods for accurate asphalt selection and pavement design. Regional imbalance in temperature growth, particularly the accelerated warming in Northern cities, underlines the urgency of integrating climate projections into transportation infrastructure planning. The specific findings of this study on the key environmental parameters can be highlighted as follows:

- Mean Annual Air Temperature (MAAT) is projected to increase steadily across all 17 cities, with Northern cities like Yellowknife expected to experience a rise of over 300%, threatening permafrost stability and subgrade integrity.
- Mean Annual Lowest Air Temperature (MALAT) is predicted to rise significantly, reducing risks of low-temperature cracking in Southern and Atlantic regions, while increasing thermal flexibility requirements in Northern design practices.

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- Mean Annual Highest Air Temperature (MAHAT) and Mean Annual Degree Days (MADD) are forecasted to increase substantially, especially in Prairie cities like Winnipeg, indicating a heightened risk of rutting and surface deformation, requiring reconsideration of binder grades and design principles.
- Mean Annual Precipitation (MAP) will increase in most cities, particularly in coastal and Western regions, raising concerns for moisture damage and subgrade weakening in pavement layers.
- While the Freezing Index is expected to decline overall, the number of freeze-thaw cycles is anticipated to intensify in transitional zones, leading to greater susceptibility to fatigue cracking and requiring enhanced drainage and material specifications.

These findings reinforce the importance of adopting climate-resilient materials, especially asphalt binder, and revising pavement design protocols to accommodate future climatic conditions.

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