Establishing Trends and Quantifying the Changes in Climatic Parameters Relevant to Pavement Performance in Manitoba

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Abstract

The parameters of environmental loads that have strong influence on pavement performance include temperature, moisture, freeze–thaw actions, and climatic extremes. Manitoba Transportation and Infrastructure (MTI) recognizes these parameters, their variations due to climate change and corresponding adaptation measures in the Pavement Assessment and Design Manual (PADM). This study was initiated to develop trends, quantify the observed and predicted changes in these parameters using historical climate data, and reflect the recommended measures, if any, in pavement design, construction and management to mitigate current and future risks. 30 years of daily weather data were obtained from Environment and Climate Change Canada for five weather stations across Manitoba to examine recent historical trends in pavement relevant climate indices.

The analysis results showed a general warming tendency in terms of annual, summer seasonal and fall seasonal average daily mean temperatures. The annual 7-day average maximum temperature is stable or declining, while the annual daily minimum temperature is increasing across all stations. In contrast, the number of very hot days is increasing at most southern and interior areas of the province, suggesting that short duration heat extremes may be occurring more often. The counts of very cold and extremely cold days are generally declining, showing a moderation trend of winter severity. The number of freeze–thaw cycles are stable or declining. However, the mid-winter thaw days are increasing, which may impact pavement performance in winter due to the interaction of engrossed moisture and traffic loads. The amount of annual precipitation is decreasing in some areas with an increased number of dry days, but it is increasing in other areas. On the other hand, fall extreme rainfall including extreme event frequency and 1-day as well as 3-day extreme precipitations are showing increasing trends in all areas. Although there were some quantifiable changes to these climatic parameters over the past 30-year period, only a few of them were found to be statistically significant at 90% confidence level. This paper presents the details of collected data, analysis, findings and recommended measures.

Introduction

Numerous research reports and field experience indicate that global climate is changing, which can affect pavement performance as pavement structures are directly exposed to environmental loads. For highway agencies, the practical needs are to assess the trends of climate indicators that matter most for pavement responses and resulting distresses, and to reflect those trends in pavement design, construction and management practices, as required. Pavements on Manitoba highways are exposed to severe and highly variable environmental conditions including extreme winter temperatures and frost action, summer heat wave, freeze-thaw cycles, spring thawing and excessive precipitation. These environmental factors have significant influence on pavement performance in terms of cracking, rutting, surface roughness, reduced structural capacity (due to seasonal reduction or loss of support), breakage and pothole development (due to moisture-related stripping of asphalt mat), settlement (due to frost-heave and swelling actions) and shoulder deterioration including washout. The progressive climate change may further aggravate these issues. In addition, since the province itself spans multiple climatic zones and different types of terrains, the changes in climate stressors are not expected to be uniform across the province or across different seasons. Therefore, a practical and local evidence-based baseline for each climate stressor, its trend or rate of change and the total amount of change, over a predefined timeframe, including its level of significance need to be developed or assessed to further the general guideline.

Manitoba Transportation and Infrastructure (MTI) currently considers the effect of past climate in pavement material selection and layer thickness design. The newly developed Pavement Assessment and Design Manual (PADM)[1] also recognizes the climate change issues, their potential impacts on asphalt concrete (AC) and portland cement concrete (PCC) surfaced pavements and recommended the corresponding adaptation measures. The manual then recommended to derive local evidence-based trends and quantify the amount or rate of changes in pavement-related climatic parameters using historical climate data, which are required to confirm whether the current assumptions are still valid and to support future refinements to pavement design inputs, drainage provisions, maintenance planning, and asset management decisions, if/as required. This study is being undertaken to assess the recent historical trends in key climatic parameters and quantify the changes that are relevant to pavement performance and climate resiliency of highways in Manitoba.

The analysis presented in this paper used data from five representative weather stations across the province, namely Winnipeg, Brandon, Dauphin, Pinawa and Thompson. The selected climatic parameters included mean annual and seasonal temperatures as well as precipitations, annual maximum, 7-day average maximum and minimum temperatures, heat and rainfall intensity indicators, freeze–thaw cycles, and mid-winter thawing events. The analysis results showed that climate change signals relevant to pavement performance are present in Manitoba, but they are not very uniform across time and place i.e., changes in vary by location or climatic zone, year and season. This paper presents the details of data, analysis and findings.

Background

The PADM is Manitoba's primary guiding document for pavement assessment and design practices. The manual uses equations from the AASHTO 1993 Pavement Design Guide[2] for structural numbers, layered design analysis and determining the structural layer coefficients. However, locally developed i.e., Manitoba specific design input parameters and performance experience or expectation are primary attributes that drive the pavement design and analysis using the PADM. The PADM recognizes that climate, drainage, traffic loads and layer materials (quality and thickness) influence the design service life and durability of pavement structures. It also emphasizes that some design inputs, engineering assumptions and related standards may need to be revisited to account for the potential impact(s) of climate change. A local climate zone based historical trend analysis of key climate indicators, that influences pavement performance, is considered to be a practical way to: i) verify whether the current assumptions are still reasonable and valid for each area of the province; ii) identify whether and where updates may be required; iii) quantity the potential change; and iv) justify the proposed updates, if any, to pavement design and management practices.

The pavement resilience framework by US Federal Highway Administration (FHWA)[3] provides a complementary perspective by defining resilience as the ability of transportation infrastructure to expect, prepare for, adapt to, withstand, respond to, and recover from disruptions. In pavement applications, relevant climate stressors include changes in temperature and precipitation, flooding and drought conditions, and freeze-thaw behaviour. These stressors can affect materials, surface performance, drainage function, structural support and maintenance needs[1,3]. This study aligns with the above stated perspective by presenting observed annual and seasonal trends that relate directly to pavement performance and practical adaptation considerations in Manitoba.

The locally derived trends of changes in climatic parameters are expected to play an important role in evaluating the current design considerations and taking appropriate measures, if required, to ensure desired performance under the changing environmental conditions. The Manitoba specific trends including seasonal patterns may also be useful for resilience planning of other highway infrastructures and assets. In addition, they can support future work on calibration, validation and refinement of climate sensitive pavement design inputs for Pavement ME Design Software. A 30-year analysis period was selected to represent 20-25-year design service life of pavement structures plus additional 5-10 years of extended performance without a rehabilitation treatment or delay in taking intervention due to budgetary limitations and/or deferred rehabilitation treatments.

Scope, Objectives and Significance

This study is being undertaken to examine the trends of climatic parameters that are relevant to pavement structures using historical records at different weather stations across Manitoba. So far, data analysis has been completed for five weather stations: Winnipeg, Brandon, Dauphin, Pinawa and Thompson. These stations were selected to provide geographic coverage of entire provincial highway network and represent the prominent variations in climatic exposures across the province. The historical weather data covering a period from 1994 to 2025 (30 years) was used in this analysis. The trends and values of different parameters have been developed at both annual and seasonal scales. The seasonal scale included summer, fall, winter and spring. The trend of a newly defined climatic parameter, called mid-winter thaw period, has also been assessed.

The objectives of this study are:

i. Establish the annual and seasonal trends of key temperature and precipitation related indicators that relevant to pavement performance in Manitoba;
ii. Compare regional differences among the selected areas, with data from representative weather stations, of the province;
iii. Quantify the amount or rate and direction (incline or decline) of changes of these selected parameters over a 30-year horizon;
iv. Interpret the engineering significance of observed changes in climate to pavement distress mechanisms and resilience;
v. Assess the engineering implications of changes to these climatic paraments on pavement design and specified materials, drainage design, construction, maintenance, preservation, rehabilitation and seasonal load management including the relevant policies; and
vi. Provide recommendations to support future refinement of PADM well as pavement management policy and climate informed decision making in pavement design/management.

The objectives of this paper are to: i) present the study method, supporting literature review, completed analyses and key findings, and ii) provide some recommendations that may contribute to improving the climate resilience of pavement structures in Manitoba. These findings and recommendations may aid MTI and other highway agencies in understanding key climatic stressors, tracking their changes over time, and incorporating climate informed inputs into pavement design, construction and management practices.

Findings from Literature Review

A literature review was undertaken to identify or confirm the climate stressors that are most relevant to pavement performance and to learn more about the degree of their impacts and adaptation measures. The literature review primarily focused on the Canadian and cold-region contexts and four climatic exposure pathways that are of prime concerns: temperature extremes, moisture exposure, freeze–thaw and mid-winter thawing behaviours, and short-duration intense rainfall events. Throughout the reviewed technical papers, the temperature and moisture were recognized as the dominant environmental parameters that significantly affect pavement performance, and several authors stressed that an increase in extremes and a shift in seasonal transition behaviours can matter as much as the changes in long term averages[4,5,6].

Saleh et al.[5] identified the rising temperature and increasing precipitation intensity as the key stressors and summarized the adaptation measures that span changes in design inputs, materials selection, drainage, monitoring, maintenance practices and agency standards. Maadani et al.[6] recommended an adaptation measure from Canadian perspective: climate resilient pavement design should be framed around the conditions likely to occur over the design life, rather than assuming historical stationarity of climatic exposure. Their discussion placed particular emphasis on heat, precipitation and freeze–thaw behaviour in local context linking these stressors to practical impacts on pavement.

Few studies provided quantitative values that directly link the changes in climatic stressors to responses of pavement structures. Sias et al.[4] reported that asphalt rutting is projected to increase by approximately 2% for every 1% increase in mean temperature. They also noted that higher temperatures accelerate asphalt ageing, which in turns increase its brittleness and cracking susceptibility over time. An increased moisture in subgrade soils can reduce the load-bearing capacity for months and, in some cases, it can halve the pavement service life. These emphasize why a pavement's responses to wet/dry conditions and its sensitivity to moisture are important considerations in pavement management and life-cycle planning. Similarly, Karam et al.[7] found that maximum temperature is a statistically significant contributor to rutting development, which supports the use of hot-extreme temperature metrics alongside the mean temperature. For cold regions, Jiang et al.[8] reported that freeze-thaw behaviour strongly influences flexible pavement roughness and long-term operation. Luo et al.[9] also concluded that freeze–thaw remains a severe durability threat in cold-region concrete pavements. These support the inclusion of seasonal transition indicators such as freeze–thaw cycles and mid-winter thaw days in all climate impact assessments. With respect to moisture and drainage, Wang et al.[10] reported that intense rainfall can contribute to waterlogging, operational safety concerns and moisture-related damage to pavements and also noted that drainage capacity may become inadequate with increased intensity of short-duration storm. Raffaniello et al.[11] observed that pavements with similar structural capacity can perform differently under warm and cold (freezing) climates, which supports localized area-based comparisons rather than treating a large region as a single climatic environment.

Taken together, the publicly available literature shows that climate effects on pavements can be discussed under four main groups of climate indicators as listed below. These four groups are consistent with the climate indicators shown in the PADM[1] and used in this study.

1. Summer temperature and hot extremes: These can affect asphalt rutting, aging and overall performance;

2. Winter temperature and seasonal shifts including changes in cold extremes, mid-winter thaws, freeze-thaw days and spring thawing: These can affect thermal cracking, seasonal loss of support and road surface roughness;
3. Precipitations and moisture including the annual precipitation and wet/dry days: These can affect subgrade moisture and pavement support; and
4. Heavy and extreme rainfall events: These can affect drainage performance, water infiltration into pavement structures, erosion and moisture related damage.

Data, Definitions and Methodology

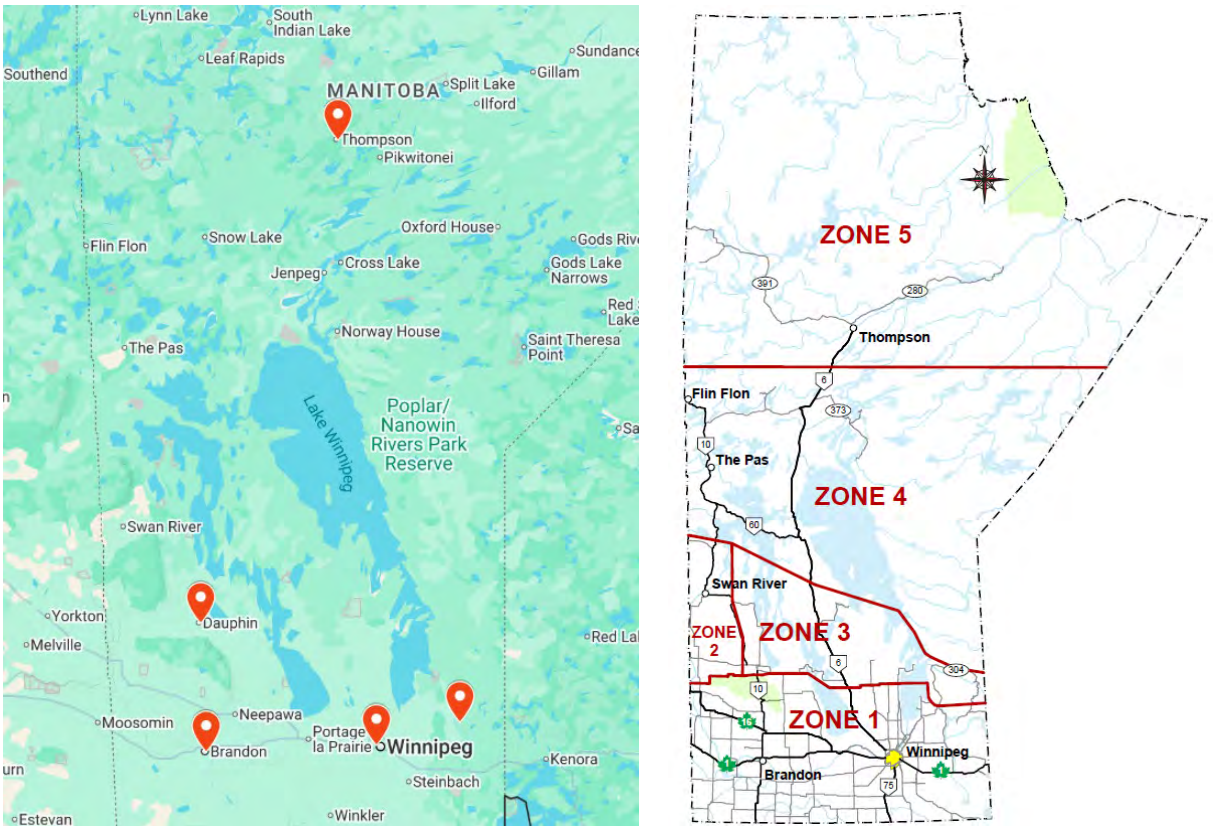
Historical daily climate data were retrieved from Environment and Climate Change Canada (ECCC) weather station records for five stations (Winnipeg, Brandon, Dauphin, Pinawa and Thompson) in Manitoba and complied together for the period from 1994 to 2025. These weather stations closely align with the practical way that MTI applies highway seasonal weights policies (Spring Road Restrictions and Winter Seasonal Weights) and associated climate zones, and MTI's administrative/operational regions (Eastern, Western, Parkland-Interlake, and Northern).

The selected weather stations also provide good geographic coverage across Manitoba and capture differences in elevation and surrounding terrain as well represent prominent weather variations across the province. Details of these stations are presented in Table 1. Figure 1 shows the geographic locations of these weather stations and different climate zones. It should be noted that Manitoba's climate zones reflect climate patterns (major factor), localized industry needs including route continuity/access and administrative ease for the annual implementation of highway seasonal weight limits.

Table 1. Details of selected weather stations

Staton	Coordinates	Elevation	Region	Geography
Winnipeg Richardson International Airport	49.9167, −97.2333	238.7 m	Eastern	Low-elevation southern prairie setting with Lake Winnipeg to the north
Brandon Airport	49.9100, −99.9519	409.4 m	Western	Higher-elevation southwestern prairie setting
Dauphin Airport	51.1000, −100.0500	304.5 m	Parkland-Interlake	North-western parkland and inter-lake setting with Lake Manitoba and Lake Dauphin to the west and Lake Winnipegosis to the north. It is also located near Duck Mountain and Riding Mountain Provincial Park
Pinawa	50.1806, −96.0583	266.7 m	Eastern	Eastern Manitoba Canadian Shield setting with Lake Winnipeg to the west
Thompson Airport	55.8033, −97.8625	224.0 m	Northen	Northern Manitoba conditions and provides coverage of the Canadian shield/boreal surrounding

Figure 1. Geographic locations of selected weather stations and Manitoba climate zones



The daily temperature and precipitation records from ECCC's Climate Data/Historical Data system were used for the computation of annual and seasonal climate indicators, analysis of their trends and quantification of their changes. The available record for each of the selected climate indicators at each weather station was reviewed for completeness before starting the above stated computation and analysis. A missing data for a variable (e.g., daily minimum, mean or maximum temperature), if any, was filled with relevant data from a nearby station with similar weather, as the selected weather station, in the same variable that was under consideration.

The climate indicators, that were used in this analysis, were selected and developed to reflect climate exposure pathways for pavement structures that are identified in the PADM and other literature related to climate impact and resilience. These include:

- Heat loading (temperature means and hot extremes);
- Cold weather exposure and thermal cycling (cold extremes, freeze–thaw cycles and mid-winter thaws);
- Moisture loading and support weakening (precipitation totals and wet/dry days); and
- Event concentration relevant to drainage and infiltration risk (short-duration precipitation extremes).

The annual and seasonal climate indicators were derived from daily temperature and precipitation data using a combination of standardized Environment and Climate Change Canada (ECCC) Core Climate Extreme Indices (Climdex)[12] and Manitoba specific definitions/thresholds. Official definitions from ECCC

were adopted where available or appropriate; for example, the definitions of wet/dry days, freeze–thaw cycles, heavy/extreme precipitations. Locally developed definitions/thresholds were used for other climate indicators such as the mid-winter thaw days and cold/hot temperature extremes to represent Manitoba specific additional climate exposures or extremes.

The computed annual and seasonal indices included the followings:

- Annual average daily mean temperature;
- Annual maximum temperature;
- Annual 7-day average maximum temperature;
- Annual minimum temperature;
- Seasonal average daily mean temperatures;
- Counts of very hot and extremely hot days;
- Counts of very cold and extremely cold days;
- Freeze–thaw cycles;
- Annual total mid-winter thaw days;
- Annual and seasonal precipitation totals;
- Annual numbers of wet and dry days; and
- Rainfall-intensity indicators including maximum 1-day and maximum 3-day precipitations and heavy and extreme rainfall event counts.

The following thresholds and ranges were used for climate extremes:

- Very hot days: Daily maximum temperatures of ≥ 32°C and < 34°C
- Extremely hot days: Daily maximum temperatures of ≥ 34°C
- Very cold days: Daily minimum temperature of ≤ −28°C and > −34°C
- Extremely cold days: Daily minimum temperature of ≤ −34°C
- Freeze–thaw cycles: Temperature changes from ≤ −1°C to > 0°C
- Heavy precipitation: Daily precipitations ≥ 10mm and < 20mm
- Extreme precipitation: Daily precipitations ≥ 20mm

The following windows were used for seasonal break-down:

- Summer: May to August
- Fall: September to November
- Winter: December to February
- Spring: March to April
- Mid-winter thaw: December 21 to February 20 (as applicable to the southern area)

The annual total mid-winter thaw days is the sum of all qualifying mid-winter thaw event durations that occurs during the specified Mid-winter Thaw Window. A qualifying mid-winter thaw event is defined as three or more consecutive days with daily maximum air temperature of > 0°C.

The trend slope of each climatic parameter was estimated using linear regression and reported as slope (i.e., change) per decade (10 years). The statistical significance of each slope was assessed using the t-test at 90% confidence interval. The selected dataset was also used to generate the summary figures/tables that are included in this paper, which include: annual mean temperature, heat related indicators, annual and seasonal precipitations, count of dry days, rainfall extremes, freeze-thaw cycles and mid-winter thaw days. The predicted change in (i.e., the trend slope of) each climate parameter over the next 30 years was assumed to be the same as that was established based on trend analysis of data from past 30 years.

Climate Trend Analysis and Results

This section presents the analysis results using summary tables (red font indicates that the values are statistically significant at 90% confidence level) and supporting figures that show the annual or seasonal variations and the overall direction of changes (increase or decrease) of various climatic parameters at each area (weather station). A change in a climatic parameter over a 30-year horizon, with respect to a baseline or reference year, can be taken as three times the value shown in the respective table.

Annual Average Daily Mean Temperature

Table 2 and Figure 2 show that there is an increasing trend of annual mean daily temperature in all areas (at all weather stations), which indicate a general warming trend across the province. However, the magnitude and rate of increase varied across different areas of Manitoba. Winnipeg has experienced the largest increase (+0.49 °C/decade) of mean daily air temperature over the last 30 years, which was followed by Dauphin (+0.47 °C/decade), Brandon (+0.42 °C/decade), Pinawa (+0.35 °C/decade) and Thompson (+0.17 °C/decade). The slopes for Winnipeg, Brandon and Dauphin are statistically significant at 90% confidence level; however, the trend slopes for Pinawa and Thompson areas are not statistically significant, but noticeable.

Table 2. Summary of changes in (trend slopes for) annual temperature indices (1994–2025)

Station	Daily Mean Temp. (°C/decade)	Min. Temp. (°C/decade)	Max. Temp. (°C/decade)	7-Day Avg. Max. Temp. (°C/decade)
Winnipeg	+0.49 (p= 0.061)	+0.89 (p= 0.128)	+0.82 (p= 0.031)	-0.05 (p= 0.873)
Brandon	+0.42 (p= 0.052)	+0.74 (p= 0.170)	-0.07 (p= 0.842)	-0.11 (p= 0.748)
Dauphin	+0.47 (p= 0.044)	+0.80 (p= 0.068)	-0.08 (p= 0.835)	-0.28 (p= 0.369)
Pinawa	+0.35 (p= 0.141)	+0.70 (p= 0.233)	+0.33 (p= 0.296)	-0.14 (p= 0.649)
Thompson	+0.17 (p= 0.48)	+1.0 (p= 0.036)	-0.31 (p= 0.396)	-0.49 (p= 0.083)

Annual Minimum Temperature

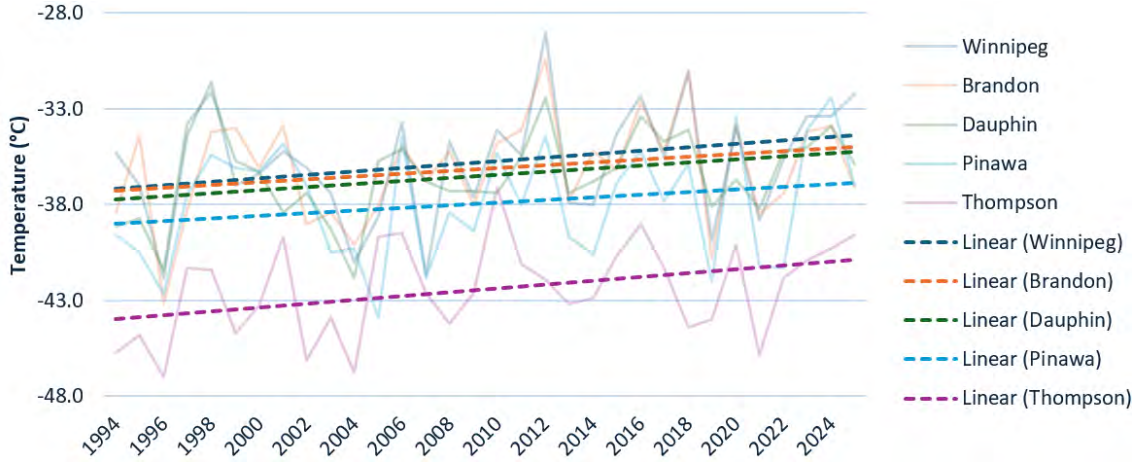
Table 2 and Figure 3 show that the annual minimum air temperature had an increasing trend over the last three decades at all five weather stations. The increase ranged from +0.70 °C/decade at Pinawa to +1.00 °C/decade at Thompson. Winnipeg (+0.89 °C/decade), Dauphin (+0.80 °C/decade) and Brandon (+0.74 °C/decade) also showed positive trends. The changes in minimum temperature are statistically significant

for Dauphin and Thompson areas only. However, the rates of increase in the minimum air temperature in other three (Winnipeg, Brandon and Pinawa) areas were considerable as well.

Figure 2. Trends of annual average daily mean air temperature (1994–2025)



Figure 3. Trends of annual minimum air temperature (1994–2025)



Annual Maximum and 7-day Average Maximum Temperatures

Table 2 and Figure 4 show that the changes in annual maximum air temperature were inconsistent among different climatic areas. Winnipeg (+0.82 °C/decade) and Pinawa (+0.33° C/decade) experienced positive slopes for annual maximum air temperature, while Brandon (−0.07 °C/decade), Dauphin (−0.08 °C/decade) and Thompson (−0.31 °C/decade) showed small negative slopes. However, only Winnipeg area showed a statistically significant increase in annual maximum air temperature. In contrast, the annual 7-day average maximum air temperature, as shown in Table 2 and Figure 5, declined at all stations (Winnipeg @−0.05 °C/decade; Brandon @−0.11 °C/decade; Dauphin @−0.28 °C/decade; Pinawa @−0.14 °C/decade; and Thompson @−0.49 °C/decade). However, only the slope for Thompon is statistically significant. The difference in trends among the temperature parameters suggest that even though the annual minimum and annual average daily mean temperatures increase, a shorter duration average (i.e., 7-day average) maximum temperature may remain stable or decline. As shown in Table 2, being an industrialized and dense urban area, Winnipeg experienced the largest increase in daily mean, annual minimum and annual maximum air temperatures, as expected.

Figure 4. Trends of annual maximum temperature (1994–2025)

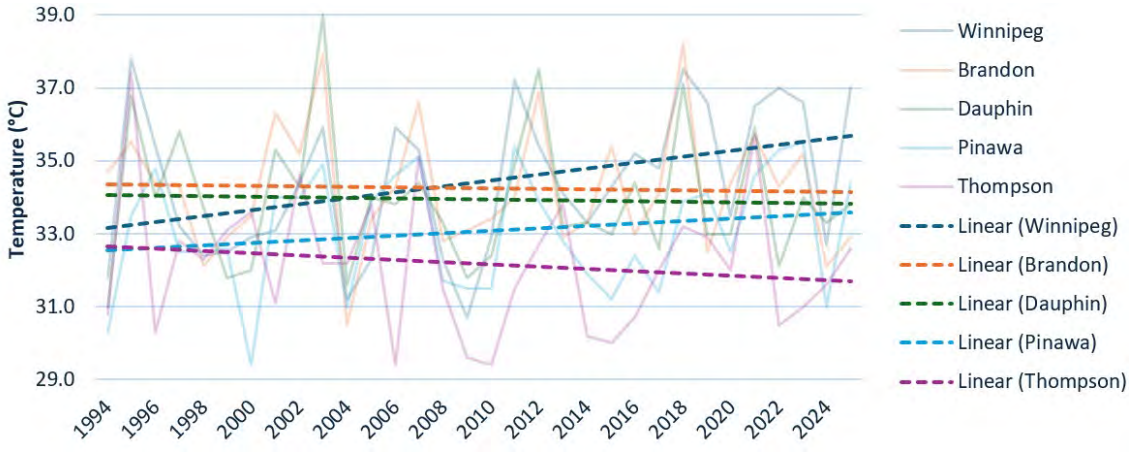
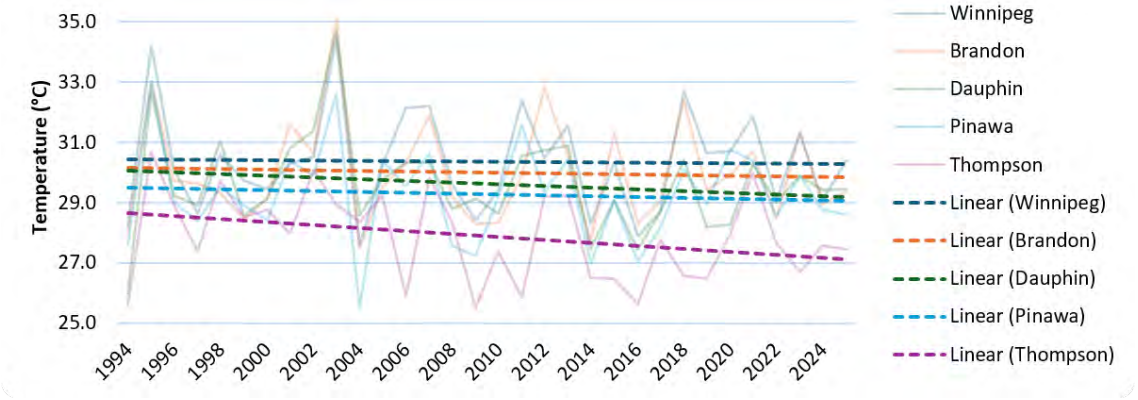


Figure 5. Trends of annual 7-day average maximum temperature (1994–2025)



Seasonal Average Daily Mean Temperature

Table 3 shows the summary of changes in (i.e., trend slopes) for seasonal average annual daily mean temperatures for all five weather stations. The summer seasonal average daily mean temperatures increased at all stations, with statistically significant (at the 90% confidence level) and similar warming trends being observed in Winnipeg (+0.40 °C/decade), Brandon (+0.38 °C/decade), Dauphin (+0.43 °C/decade) and Pinawa (+0.38 °C/decade). The fall daily mean temperatures also increased across all stations, with statistically significant warming trends in Winnipeg (+0.68 °C/decade) and Brandon (+0.59 °C/decade). Although positive trend slopes were also observed in Dauphin, Pinawa, and Thompson, these trends were not statistically significant, but noticeable. Trend slopes for the winter daily mean temperatures were inconstant among the selected climatic areas with small increase or decrease and none of them were statistically significant. The spring daily mean temperatures generally increased across the province, with the largest warming trends being observed in Brandon (+0.42 °C/decade) and Thompson (+0.33 °C/decade); however, none of the spring trends were statistically significant.

The increasing trend in annual average daily mean temperature, as discussed earlier, indicate a general warming trend across Manitoba. However, the seasonal temperature trends suggest that the observed increase in annual mean temperature is primarily associated with rising summer and fall temperatures.

Table 3. Trend slopes for seasonal average annual daily mean temperature (1994–2025)

Station	Summer Mean Temp. (°C/decade)	Fall Mean Temp. (°C/decade)	Winter Mean Temp. (°C/decade)	Spring Mean Temp. (°C/decade)
Winnipeg	+0.40 (p=0.046)	+0.68 (p=0.054)	-0.04 (p=0.939)	+0.17 (p=0.547)
Brandon	+0.38 (p=0.033)	+0.59 (p=0.074)	+0.02 (p=0.974)	+0.42 (p=0.122)
Dauphin	+0.43 (p=0.021)	+0.58 (p=0.133)	+0.05 (p=0.908)	+0.27 (p=0.419)
Pinawa	+0.38 (p=0.062)	+0.42 (p=0.242)	+0.15 (p=0.669)	+0.03 (0.935)
Thompson	+0.12 (p=0.492)	+0.57 (p=0.122)	-0.29 (p=0.596)	+0.33 (p=0.233)

Number of Very Hot and Extremely Hot Days

Table 4 shows that the annual number of very hot days increased at southern and interior weather stations, with the largest increase occurring at Winnipeg (+0.85 days/decade) over the past 30 years, which was followed by Dauphin (+0.37 days/decade), Pinawa (+0.32 days/decade) and Brandon (+0.21 days/decade). The northern area (Thompson) showed a small negative slope (−0.15 days/decade) i.e., a decline in the number of very hot days. However, none of the trend slopes for very hot day is statistically significant, but the increase for Winnipeg is noticeable.

Table 4. Summary of trend slopes for annual temperature extremes (1994–2025)

Station	Very Hot Days (days/decade)	Extreme Hot Days (days/decade)	Very Cold Days (days/decade)	Extreme Cold Days (days/decade)
Winnipeg	+0.85 (p= 0.138)	+0.35 (p= 0.266)	-1.30 (p= 0.067)	-0.21 (p= 0.229)
Brandon	+0.21 (p= 0.578)	-0.20 (p= 0.521)	-0.98 (p= 0.238)	-0.23 (p= 0.184)
Dauphin	+0.37 (p= 0.472)	-0.37 (p= 0.145)	-0.74 (p= 0.257)	-0.21 (p= 0.142)
Pinawa	+0.32 (p= 0.423)	+0.19 (p= 0.149)	-0.63 (p= 0.429)	-0.09 (p= 0.337)
Thompson	-0.15 (p= 0.360)	+0.04 (p= 0.752)	+0.14 (p= 0.935)	-1.49 (p= 0.034)

Table 4 and Figure 6 show mixed trends for the annual counts of extremely hot days. Winnipeg (+0.35 days/decade) and Pinawa (+0.19 days/decade) show a positive slope, while Brandon (−0.20 days/decade) and Dauphin (−0.37 days/decade) show negative slopes and Thompson shows a near-zero positive slope (+0.04 days/decade). None of the trend slopes is statistically significant at 90% confidence level. Winnipeg showed the largest increase in very hot and extreme hot days.

Number of Very Cold and Extreme Cold Days

Table 4 and Figure 7 show declining trends of the annual number of very cold days in all areas, except for Thompson. The rates of decline over the last 30 years were −1.30 days/decade in Winnipeg, −0.98 days/decade in Brandon, −0.74 days/decade in Dauphin and −0.63 days/decade in Pinawa. In Thompson area, there was a small increase (+0.14 days/decade) in the number of very cold days. However, only the trend slope for Winnipeg is statistically significant.

Figure 6. Trends of annual number of extreme hot days (1994–2025)

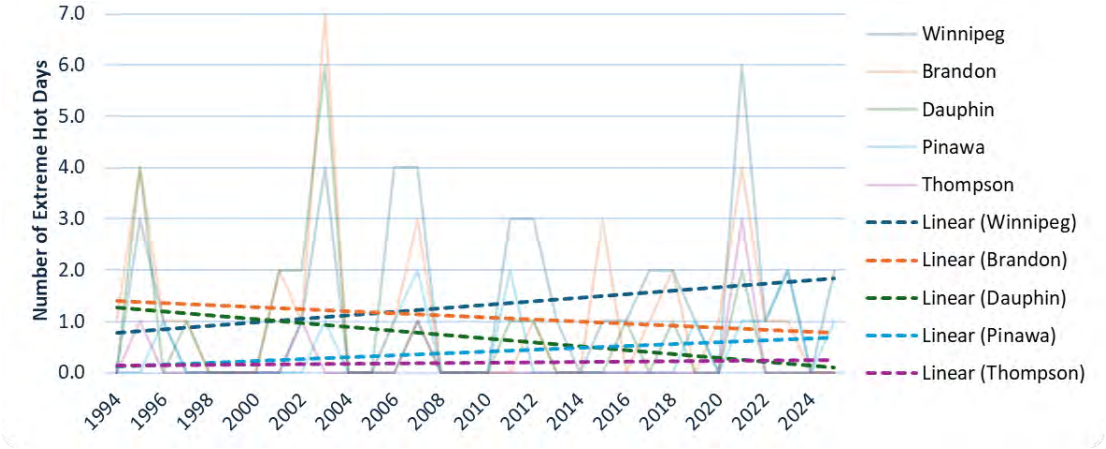


Figure 7. Trends for the annual number of very cold (days (1994–2025)

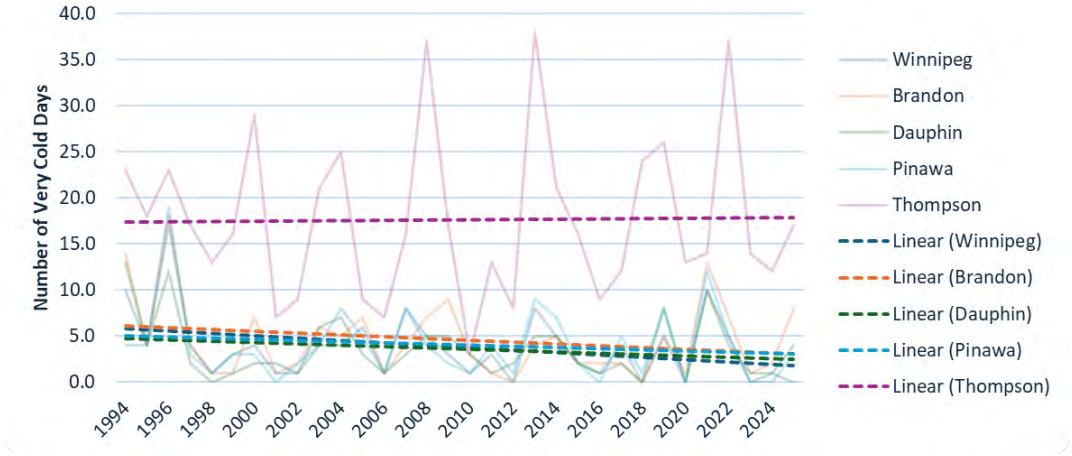


Figure 8. Trends for the annual number of extreme cold days (1994–2025)

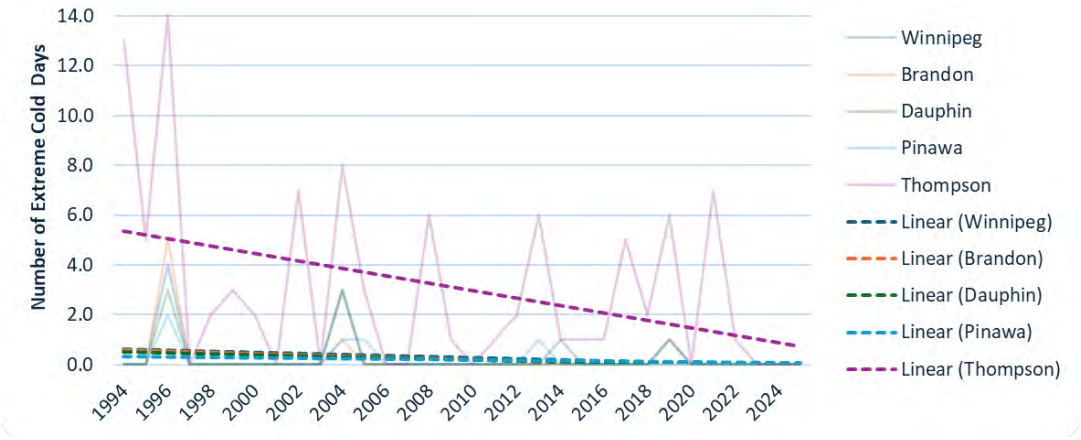


Table 4 and Figure 8 (above) show that the annual number of extremely cold days declined at all stations over the past three decades. The largest or sharp reduction has occurred at Thompson (−1.49 days/decade), which is a statistically significant decrease at 90% confidence level. At other weather

stations, there were insignificant decrease in the number of extremely cold days. The reduction of very cold and extreme cold days may also have contributed to the increase in annual average daily mean temperature in all areas.

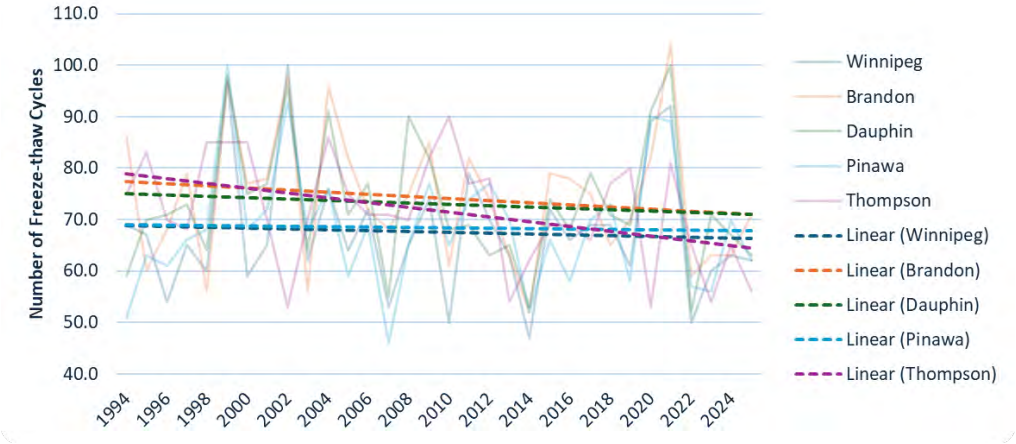
Number of Freeze-thaw Cycles

Table 5 shows that there have been declining trends of the annual number of freeze–thaw cycles across all weather stations over the past three decades. The largest decline was noted for Thompson (−4.65 cycles/decade), which was followed by Dauphin, Brandon, Winnipeg and Pinawa. Only the trend slope for Thompson showed a statistically significant decline in the number of freeze-thaw cycles. All other stations showed insignificant decline. Figure 9 shows that the number of freeze–thaw cycles varied substantially from year to year, but the long-term trends are downward at all areas.

Table 5. Trend slopes for annual number of freeze–thaw cycles and mid-winter thaw days (1994–2025)

Station	Freeze-thaw Cycles (cycles/decade)	Mid-Winter Thaw Event Days (days/decade)
Winnipeg	-0.81 (p= 0.747)	+0.96 (p= 0.165)
Brandon	-1.21 (p= 0.417)	+0.95 (p= 0.172)
Dauphin	-1.28 (p= 0.604)	+0.56 (p= 0.503)
Pinawa	-0.34 (p= 0.886)	+0.29(p= 0.717)
Thompson	-4.65 (p= 0.018)	-0.05 (p= 0.880)

Figure 9. Trends of annual freeze-thaw cycle for the five stations (1994–2025)



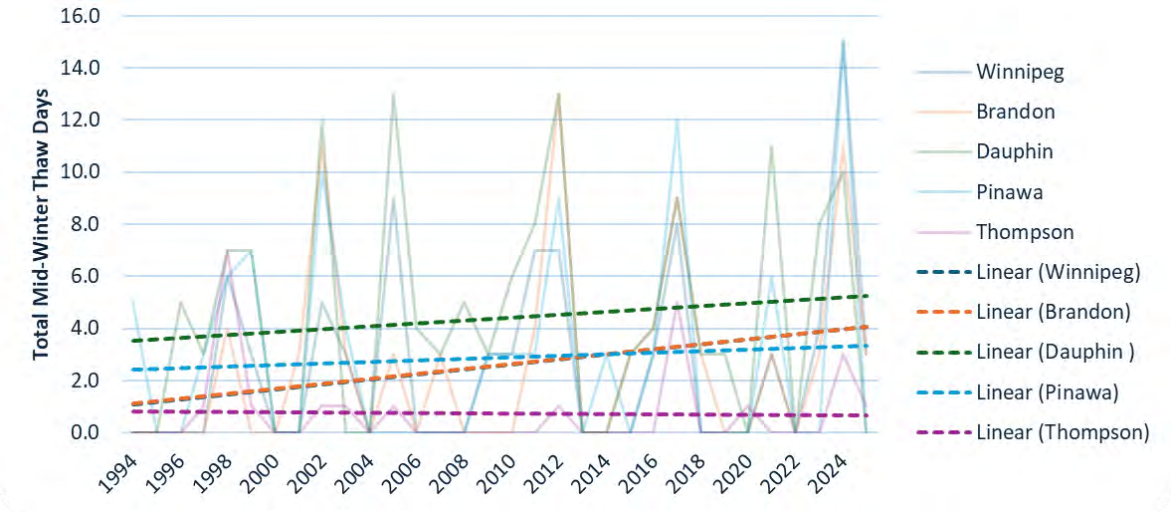
Mid-winter Thaw Days

Table 5 also presents the trend slopes of the number of annual total mid-winter thaw days. It shows that there were increase in the total number of mid-winter thaw days at Winnipeg (+0.96 days/decade) and Brandon (+0.95 days/decade), Dauphin (+0.56 days/decade) and Pinawa (+0.29 days/decade). However, none of the trend slopes are statically significant at 90% confidence level. Thompson experienced an insignificant and negligible decline in the total number of mid-winter thaw days.

Figure 10 shows that the increases in the number of mid-winter thaw days in Winnipeg, Brandon, Dauphin and Pinawa were driven by intermittent years with higher number of warm days or events in winter. This

pattern is troublesome for winter seasonal load management practices because of the sporadic amplified damage to pavement surface layer with increased weight allowances during winter season. The increasing trend of mid-winter thaw days is also concerning because it has potential for increased thaw weakening and moisture related damage during the winter and early spring seasons despite the reduced damage to pavements due to decline in the number of annual freeze–thaw cycles.

Figure 10. Trends of annual mid-winter thaw days (1994–2025)



Total Annual Precipitation and Number of Wet/Dry Days

Table 6 and Figures 11-12 show that the total annual precipitation and number of wet/dry days experienced clear difference among geographic areas over the last 30 years. Winnipeg area has experienced a statistically significant decline in annual precipitation (−50.10 mm/decade) together with a statistically significant decrease in the annual number of wet days (−10.35 days/decade) and corresponding increase in the annual number of dry days (+8.32 days/decade). Brandon has also experienced a significant decline in the total annual precipitation (−30.67 mm/decade). However, the trend slopes of the number of wet days (−5.37 days/decade,) and dry days (+4.04 days/decade) are not statistically significant.

Table 6. Trend slopes for total annual precipitation, wet/dry days and heavy/extreme precipitation events (1994–2025)

Station	Total Annual Precipitation (mm/decade)	Annual Wet Days (days/decade)	Annual Dry Days (days/decade)	Annual Heavy Precipitation (events/decade)	Annual Extreme Precipitation events/decade)
Winnipeg	-50.10 (p= 0.035)	-10.35 (p= 0.001)	+8.32 (p= 0.007)	-0.80 (p= 0.283)	-0.42 (p= 0.369)
Brandon	-30.67 (p= 0.050)	-5.37 (p= 0.128)	+4.04 (p= 0.266)	-1.38 (p= 0.063)	-0.24 (p= 0.555)
Dauphin	+30.81 (p= 0.048)	+10.71 (p= 0.015)	-1.67 (p= 0.793)	+0.95 (p= 0.088)	+0.31 (p= 0.392)
Pinawa	-20.20 (p= 0.475)	+4.24 (p= 0.557)	-4.84 (p= 0.495)	-0.44 (p= 0.568)	-0.41 (p= 0.388)
Thompson	+4.60 (p= 0.827)	+2.3 (p= 0.493)	-2.73 (p= 0.427)	+0.59 (p= 0.392)	-0.24 (p= 0.542)

As shown in Table 6, Dauphin area has experienced statistically significant increase in total annual precipitation (+30.81 mm/decade) as well as the annual number of wet days (+10.71 days/decade), while the change in the number of dry days (−1.67 days/decade) is not statistically significant at 90% confidence level. Pinawa showed insignificant trend slopes for the total annual precipitation (−20.20 mm/decade), number of wet days (+4.24 days/decade) and dry days (−4.84 days/decade). Thompson area has remained comparatively stable in terms of total annual precipitation (+4.60 mm/decade) and the number wet as well as dry days with minor changes over a decade. There was statistically significant decrease in the number of heavy precipitation events in Brandon and increase in Dauphin areas. The changes in heavy precipitation events in other areas and the extreme precipitation events any area were not significant.

Figure 11 Trends of total annual precipitation (1994–2025)

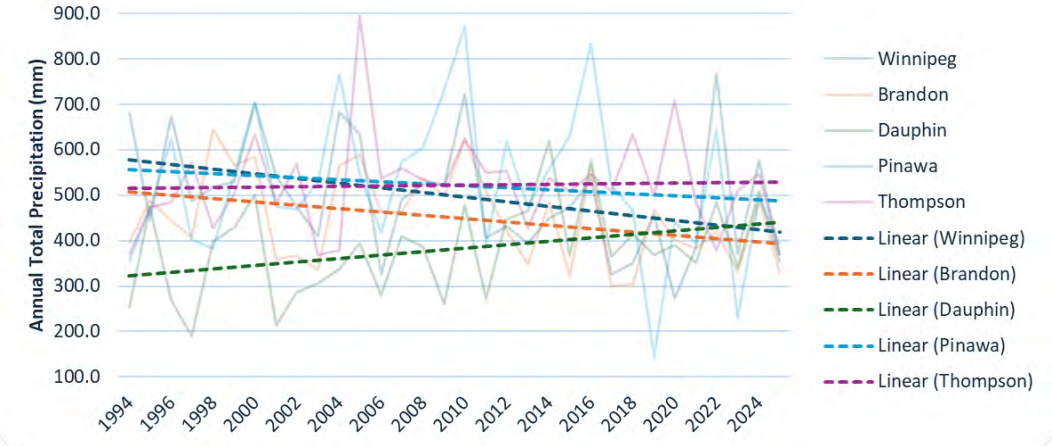
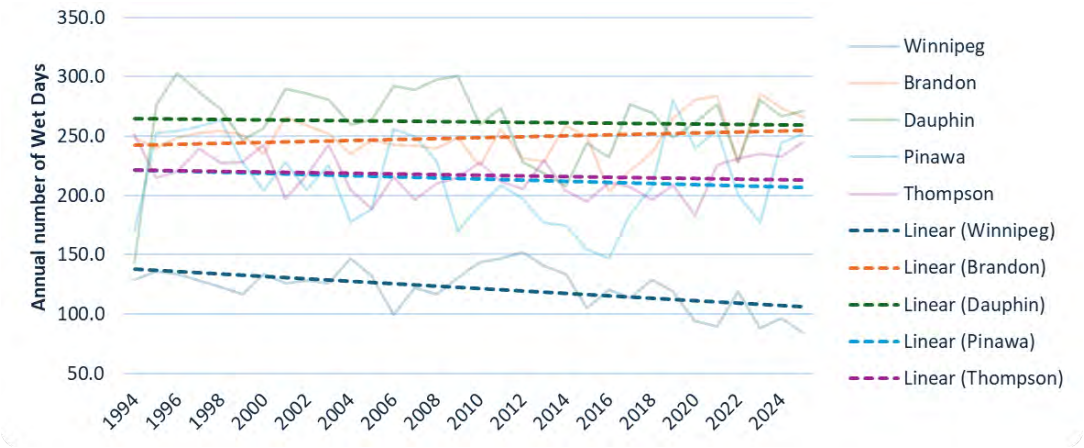


Figure 12. Trends of annual number of wet days (1994–2025)



Seasonal Trends of Precipitation

Tables 7, 8 and 9 present the summary of trend slopes for summer, fall, winter and spring seasonal precipitations over the last three decades. They are explained below:

Summer (May-August): Table 7 shows that Winnipeg, Brandon, Pinawa and Thompson had declining trends of summer total precipitation @−28.0 mm/decade, −15.2 mm/decade, −15.8 mm/decade and

−12.7 mm/decade, respectively; while Dauphin experienced an increasing trend of +6.9 mm/decade. However, none of these trends are statistically significant at 90% confidence level.

Table 7. Summer and fall precipitation, and rainfall-intensity trend slopes (1994–2025)

Station	Summar Precipitation (mm/decade)			Fall Precipitation (mm/decade)		
	Total	1-day	3-day	Total	1-day	3-day
Winnipeg	-28.0 (p= 0.122)	-5.5 (p= 0.068)	-7.4 (p= 0.017)	+4.3 (p= 0.636)	+3.6 (p= 0.089)	+2.1 (p= 0.309)
Brandon	-15.2 (p= 0.337)	+5.6 (p= 0.251)	+1.4 (p= 0.797)	-4.7 (p= 0.559)	-0.06 (p= 0.982)	-1.2 (p= 0.630)
Dauphin	+6.9 (p= 0.599)	+0.5 (p= 0.842)	-9.3 (p= 0.050)	+12.4 (p= 0.151)	+2.8 (p= 0.285)	-2.3 (p= 0.594)
Pinawa	-15.8 (p= 0.439)	-5.1 (p= 0.198)	-8.8 (p= 0.026)	-9.0 (p= 0.269)	-2.5 (p= 0.233)	-4.7 (p= 0.076)
Thompson	-12.7 (p= 0.491)	-6.4 (p= 0.028)	-8.1 (p= 0.005)	+5.9 (p= 0.410)	-1.1 (p= 0.529)	-3.4 (p= 0.065)

Table 8. Winter and spring precipitation, and rainfall-intensity trend slopes (1994–2025)

Station	Winter Precipitation (mm/decade)			Spring Precipitation (mm/decade)		
	Total	1-day	3-day	Total	1-day	3-day
Winnipeg	-13.0 (p= 0.004)	-1.9 (p= 0.092)	-4.0 (p= 0.010)	-4.7 (p= 0.401)	-1.5 (p= 0.352)	-4.4 (p= 0.041)
Brandon	-11.9 (p<0.001)	-1.4 (p= 0.089)	-3.2 (p= 0.010)	-4.9 (p= 0.255)	-1.2 (p= 0.356)	-2.6 (p= 0.060)
Dauphin	+13.1 (p<0.001)	+2.7 (p<0.001)	+2.3 (p= 0.006)	+4.6 (p= 0.330)	+2.1 (p= 0.153)	+1.1 (p= 0.498)
Pinawa	+9.0 (p= 0.190)	-0.4 (p= 0.647)	-0.9 (p= 0.325)	+3.2 (p= 0.641)	-0.9 (p= 0.678)	-2.6 (p= 0.286)
Thompson	+5.5 (p= 0.148)	+0.2 (p= 0.795)	-1.4 (p= 0.150)	+5.9 (p= 0.233)	+2.2 (p= 0.101)	+1.0 (p= 0.446)

Table 9. Summary of seasonal heavy and extreme precipitation events trend slopes (1994–2025*)*

Station	Summer (events/decade)		Fall (events/decade)		Winter (events/decade)		Spring (events/decade)	
	Heavy	Extreme	Heavy	Extreme	Heavy	Extreme	Heavy	Extreme
Winnipeg	+0.30 (p= 0.556)	-0.66 (p= 0.096)	-0.49 (p= 0.180)	+0.39 (p= 0.021)	-0.24 (p= 0.017)	-0.06 (p= 0.324)	-0.20 (p= 0.368)	-0.03 (p= 0.775)
Brandon	-0.66 (p= 0.250)	-0.15 (p= 0.677)	-0.06 (p= 0.817)	+0.01 (p= 0.955)	-0.33 (p= 0.020)	+0.00 (p= 1.000)	-0.27 (p= 0.146)	+0.01 (p= 0.868)
Dauphin	+0.65 (p= 0.198)	+0.19 (p= 0.463)	+0.17 (p= 0.531)	+0.04 (p= 0.815)	+0.13 (p= 0.120)	+0.00 (p= 1.000)	-0.01 (p= 0.969)	+0.08 (p= 0.168)
Pinawa	-0.65 (p= 0.239)	-0.08 (p= 0.854)	-0.04 (p= 0.900)	-0.30 (p= 0.090)	-0.05 (p= 0.668)	+0.00 (p= 1.000)	+0.29 (p= 0.170)	-0.03 (p= 0.814)
Thompson	-0.09 (p= 0.874)	-0.11 (p= 0.764)	+0.34 (p= 0.323)	-0.15 (p= 0.505)	-0.02 (p= 0.877)	+0.00 (p= 1.000)	+0.36 (p= 0.086)	+0.03 (p= 0.775)

The summer rainfall-intensity indicators show that Winnipeg experienced a statistically significant decrease in summer maximum 1-day and 3-day precipitations (-5.5 and −7.4 mm/decade, respectively). Thompson also experienced a statistically significant decrease in both maximum 1-day (−6.4 mm/decade) and maximum 3-day precipitation (−8.1 mm/decade) precipitations. Dauphin and Pinawa experienced statistically significant decrease in summer maximum 3-day precipitations (-9.3 and −8.8 mm/decade, respectively). The changes for Brandon were statistically insignificant.

Table 9 shows that the changes in summer heavy and extreme event counts are not statistically significant in any area, except for the trend slope of extreme events in Winnipeg. Overall, the precipitation trends suggest a progressively drier summer in most areas including decline in short-duration total precipitations.

Fall (September-November): The trend data in Table 7 shows that fall total precipitation has increased in Winnipeg (+4.3 mm/decade), Dauphin (+12.4 mm/decade) and Thompson (+5.9 mm/decade), but decreased in Brandon (-4.7 mm/decade) and Pinawa (-9.0 mm/decade). However, none of them is not statistically significant. Fall maximum 1-day precipitation had a statistically significant increase in Winnipeg (+3.6 mm/decade), but no significant increase or decrease in other areas. Fall maximum 3-day precipitation showed a declining trends in all areas, except for Winnipeg. However, only the declines in Pinawa and Thompson were statistically significant.

Table 9 shows a statistically significant increase in fall season extreme rainfall event frequency in Winnipeg and decline in Pinawa. The trends of extreme rainfall events at other weather stations and the mixed trends of fall heavy rainfall events among the selected stations were not statistically significant.

Winter (December-February): The statistics presented in Table 8 show strong and statistically significant signals for changes in winter precipitation at multiple areas. Winnipeg and Brandon have experienced statistically significant declines of winter total precipitation and maximum 1-day as well as 3-day precipitations. In contrast, Dauphin has experienced statistically significant increase in winter total precipitation and maximum 1-day as well as 3-day precipitations. The increase and/or decrease in winter total precipitation and maximum 1-day as well as 3-day precipitations in Pinawa and Thomson are not statistically significant.

Table 9 shows that the winter heavy precipitation event counts decreased significantly at Winnipeg (−0.24 events/decade) and Brandon (−0.33 events/decade) weather stations. Dauphin has experienced a considerable increase in heavy precipitation events. The changes in winter extreme precipitation event counts are not statistically significant for any areas. Overall, the winter seasonal precipitation trends show that the direction and significance of change vary by station: statistically significant dryer winter in Winnipeg and Brandon versus statistically significant wetter winter in Dauphin area. The increase in winter total precipitation in Dauphin area is associated with increase in short-term (1-day and 3-day) maximum precipitations.

Spring (March-April): Table 8 shows that the trend slopes for spring total precipitation are not statistically significant at any weather station (Winnipeg −4.7 mm/decade, Brandon −4.9 mm/decade, Dauphin +4.6 mm/decade, Pinawa +3.2 mm/decade), except for the increasing trend at Thompson (+5.9 mm/decade). The trend slopes for spring short-term precipitation intensity (1-day and 3-day maximums) are also generally not statistically significant, except for the increase in 3-day maximum precipitations in Winnipeg and Brandon areas. Table 9 shows that the trend-slopes for spring heavy and extreme precipitation event counts are not statistically significant at any station, except for the increasing trend of heavy precipitation events in Thompson.

Summary of Seasonal Trends: The statistics presented in Tables 7 and 8 show that the changes in seasonal precipitation trends are not uniform across Manitoba. In general, the province is experiencing a progressively drier weather, with the exception of Parkland-Interlake area (represented by Dauphin weather station). Parkland-Interlake area is experiencing a progressively wetter weather. Table 9 further shows that statistically significant changes in seasonal heavy and extreme precipitation events are limited and area-specific with a high variation among the precipitation intensity indicators and seasons.

Summary of Findings and Assessment

Several climatic parameters affect pavement performance. Accordingly, Manitoba's pavement related climatic parameters were assessed under four key mechanisms: heat loading, cold weather exposure and thermal cycling, moisture loading and support weakening and event concentration relevant to drainage and infiltration risk. The trend analysis of annual climatic parameters showed the general direction as well as magnitude of pavement relevant climate change in Manitoba. The trend analysis for seasonal parameters showed when some of those changes matter most in terms of an adverse impact on pavement performance. This distinction is important because many pavement distresses depend on seasonal climatic exposures including the event frequency and extremes, and the changes in pavement support conditions, not just on the annual averages alone. The key findings from the analysis and their implications are discussed below:

1. The increasing trends of annual average daily mean temperature in all areas, although not significant in some areas but noticeable, seem to be primarily driven by increase of summer and fall seasonal daily mean temperatures in all areas.
2. The increasing mean temperatures may improve or degrade (there are mixed interpretation about the impact) the fatigue cracking resistance of AC layer; however, it is likely to cause increased aging of asphalt binders and ultimately, reduced resistance to cracking.
3. The increasing trends of minimum temperature and declining trends of very cold and extreme cold days are beneficial in terms of AC mix and binder resistance to thermal cracking. These may allow for the use of stiffer (higher low temperature grades) asphalt binders in some areas.
4. Although there were increases in the summer maximum temperature (significant in Winnipeg and noticeable in Pinawa), number of very hot days (only significant in Winnipeg) and/or extreme hot days (not significant in any area) in some areas over the past 30 years, there have been declining trends of 7-day average maximum temperatures in all areas (negligible in Winnipeg and significant in Thompson). The reduction of 7-day average maximum temperature seems to be associated with milder temperature in day(s) following and/or preceding the short duration very hot and extreme hot events. These trends have to be carefully assessed and considered in asphalt mix and binder selection because the increased maximum temperature, even for shorter than 7-day duration, very hot and extreme hot events can also cause asphalt softening, densification and surface ageing resulting in increased rutting, bleeding and ravelling. The increased maximum temperature and number of very hot and/or extremely hot days can cause drying shrinkage (at early stage), curling and expansion of concrete pavement leading to cracking and blow-ups. Concrete mix design and joint layout designs should factor in these potential issues.
5. There have been declining trends of the annual number of freeze–thaw cycles in all areas (significant for Thompson only), which is beneficial to all pavement structures. However, the

increasing trends of mid-winter thaw days are concerning because the water from melted snow/ice can ingress into cracks, joints, shoulders and the near surface base/subbase layers during a period when the pavement structure would normally be expected to remain frozen. These may result in potholes development in AC pavements, joint damage in concrete pavements, softening of pavement shoulders and weakened base support conditions. If a thawing event is followed by re-freezing, the frozen trapped water can contribute to localized heaving, resulting in additional cracking and potholes development. The mid-winter thawing can also pose challenge in managing the winter seasonal weight allowances and amplified damage to the pavement surface layers.

6. The total annual precipitations are significantly declining in Winnipeg, Brandon and Pinawa and significantly increasing in Dauphin, while it was showing a smaller increase in Thompon. These indicate an area specific pattern of change in total precipitation. The declines for Winnipeg and Brandon were associated with increase in the number of dry days (significant in Winnipeg) and the reduction of heavy (significant in Brandon) and extreme precipitation events. The decline in total annual precipitation in Pinawa area was associated with reduction of heavy and extreme precipitation events. Pinawa has also experienced increasing number of wet days. The increasing trend of total annual precipitation in Dauphin area seems to be associated with increased heavy (significant) and extreme rainfall events. An increased amount or frequency of rainfalls can accelerate moisture related stripping of AC mixes, weaken the base, subbase and subgrade supports, and cause loss of support due to pumping out of fines from underneath the pavement joints and cracks. Alternatively, the increased number of dry days can cause increased oxidation of asphalt binders; however, the reduced moisture related damage may offset the added damage due to binder oxidation.

7. Winnipeg area has experienced significant increase in 1-day maximum precipitation in the Fall together with a significant increase in the number of extreme rainfall events over the past three decades. Thompson area has experienced significantly increased number of heavy rainfall events in Spring. Dauphin area has experienced significant increase in total precipitations in Winter together with significant increase in 1-day and 3-day maximum precipitations and a considerable increase in the number of heavy precipitation events. Pinawa and Thompson have also experienced considerable increase in precipitation in Winter. The increased seasonal, 1-day maximum and 3-day maximum precipitations, and heavy and extreme precipitation events can stress the drainage capacity, wet weather road safety (hydroplaning risk), skidding, increased moisture infiltration through cracks, shoulder erosion, embankment stability and moisture related weakening of pavement support.

8. Although a number of trend slopes are not statistically significant at 90% confidence level, some of them may be considerable because the accumulated change from a reference year over several decades could be large. Pavement and drainage performance information should be gathered and their relation to changing climate indices should be verified.

9. The accumulated changes to a climatic parameter should be calculated with respect to a reference year and measures should be taken to address the combined adverse impacts of changing inter-related climatic parameters on pavement structures and drainage, where applicable.

Recommendations

The observed trends of various climatic parameters indicate that the adaptation measures in Manitoba should be climatic zone/area specific. The complex and interactive behaviours of climate changes and their potential impacts should be taken into consideration in all proposed measures to address all potential failures and safety issues. The following recommended measures may translate the observed annual, seasonal and short-term signals into practical actions and are consistent with the adaptation logic reflected in the PADM and other climate resilience guidance:

i. Apply climate zone/area specific and surface-type-sensitive measures considering the composite impacts, rather than uniform network-wide actions;
ii. Review, and if required, increase the asphalt binder high temperature grade and SuperPave asphalt mix traffic loading category for routes/locations with increasing hot day counts and/or daily maximum temperature exposures;
iii. Use polymer modified asphalt binder to reduce binder aging and oxidation due to increased temperature and hot days. Add anti-stripping agent(s), if the quality of aggregates is marginal, to resist the increased moisture related stripping potential in areas with increased precipitations and moisture exposures;
iv. Consider earlier or more frequent preservation treatments where repeated short-duration very and/or extremely high temperature events may accelerate asphalt binder oxidation, surface hardening, bleeding and rutting susceptibility.
v. Review concrete pavement joint spacing, mix design and curing practices to control early age shrinkage, expansion, curling and warping where high temperature and moisture exposures may increase cracking and blow up risks;
vi. Consider rapid removal of snow and hauling away or pushing further out/down from the road shoulders, specially in advance of the potential thawing events, to reduce potential for moisture ingress into pavements and supporting layers as well as subgrade;
vii. Integrate the increased mid-winter thaw related weakened support into pavement design, where required;
viii. Reduce air voids in AC mixes (increase compaction of AC mat) to reduce the potential for water ingress into the AC layer in areas with increasing precipitation;
ix. Prioritize crack sealing and surface as well as shoulder drainage maintenance where thawing and refreezing cycles can increase moisture ingress, which can cause the development of potholes, localized instability and cracking;
x. Review cross-slope, ditch as well as culvert capacity, shoulder and embankment stability, and embankment drainage to ensure rapid conveyance of runoff in locations with increased precipitation intensity and/or extreme precipitation events. Consider pavement support and embankment stabilization measures, where required, to avoid erosion and washouts;
xi. Consider using high friction surface course or surface treatment at locations with increased intensity of precipitation, extreme precipitation events, mid-winter thaw days and number of wet days to enhance skid resistance and highway safety; and
xii. Review the geometric, embankment and drainage design standards, maintenance and seasonal load management policies to address area-specific requirements, where applicable.

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