Dynamical Downscaling of Temperature Variations over the Canadian Prairie Provinces under Climate Change

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Abstract: In this study, variations of daily mean, maximum, and minimum temperature (expressed as $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$) over the Canadian Prairie Provinces were dynamically downscaled through regional climate simulations. How the regional climate would increase in response to global warming was subsequently revealed. Specifically, the Regional Climatic Model (RegCM) was undertaken to downscale the boundary conditions of Geophysical Fluid Dynamics Laboratory Earth System Model Version 2M (GFDL-ESM2M) over the Prairie Provinces. Daily temperatures (i.e., $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$) were subsequently extracted from the historical and future climate simulations. Temperature variations in the two future periods (i.e., 2036 to 2065 and 2065 to 2095) are then investigated relative to the baseline period (i.e., 1985 to 2004). The spatial distributions of temperatures were analyzed to reveal the regional impacts of global warming on the provinces. The results indicated that the projected changes in the annual averages of daily temperatures would be amplified from the southwest in the Rocky Mountain area to the northeast in the prairie region. It was also suggested that the projected temperature averages would be significantly intensified under RCP8.5. The projected temperature variations could provide scientific bases for adaptation and mitigation initiatives on multiple sectors, such as agriculture and economic sectors over the Canadian Prairies.

Keywords: dynamical downscaling; projected variations; Canadian Prairies; global warming

1. Introduction

Climate warming is one of the most significant challenges currently facing the globe and humanity. Consequently, assessment of climate change impacts is needed to support adaptation and mitigation strategies [1–9]. Such impacts are commonly investigated based on future climate projections simulated by global climate models (GCMs) under multiple scenarios [10–13]. However, the mechanisms and processes of climate change at regional scales cannot be comprehensively reflected by these coarse-resolution projections [14–18]. Therefore, the development of fine-resolution climate projections is needed to explore the climate change impacts within a regional context.

Climate projections of GCMs have been primarily employed in previous studies to examine climate variations over the Canadian region in response to global warming [19–30]. More recently, several studies [31–34] have attempted to dynamically downscale GCMs over the Canadian prairies based on regional climate models (RCMs). For example, PaliMazumder et al. [33] projected changes in short- and long-term drought characteristics over the Canadian Prairies by using an ensemble of ten Canadian RCM (CRCM)
simulations. These previous studies have demonstrated that RCMs have advantages in reflecting the climatology processes at local scales as compared to GCMs [9,35]. For instance, Zhou et al. [9] developed a dynamical-coupled downscaling approach and demonstrated its advantages in capturing the regional details.

RCMs can resolve more detailed features such as mountain ranges, coastal zones, and soil properties, which are consistent with physical mechanisms in GCMs. As a consequence, dynamical downscaling can provide climate variables at a fine spatio-temporal resolution in order to support a better understanding of climate change impacts within the global warming context [36]. However, there have been few reports of dynamic downscaling of daily temperatures over the Canadian Prairie Provinces at a high spatial resolution (e.g., 25 km) under the representative concentration pathways (RCPs).

In addition, the Canadian Prairie Provinces are affected by the Rocky Mountains and undulating prairies. Such complex topography will have a significant impact on the local climate conditions in this region. The observations in the Rocky Mountain region are sparse due to the complex topography. Initiatives of regional climate downscaling can provide gridded climatic information with a fine spatio-temporal resolution, supporting mitigation and adaptation of the severe impacts of climatic changes. The development of a fine-resolution climate fluctuations is thus essential to comprehensively reveal the potential impacts of climate change on the Prairie Provinces.

Therefore, the objective of this study is to examine how the regional climate over the Canadian Prairie Provinces will increase in response to global warming through the development of climate projections based on RCM. In detail, the Regional Climatic Model (RegCM) will be undertaken to downscale the boundary conditions of Geophysical Fluid Dynamics Laboratory Earth System Model Version 2M (GFDL-ESM2M). Daily mean, maximum, and minimum temperature are subsequently extracted from the historical and future climate simulations. Temperature variations in the two future periods (i.e., 2036 to 2065 and 2065 to 2095) are then investigated relative to the baseline period (i.e., 1985 to 2004). The spatial temperature distributions will be analyzed to reveal the impacts of global warming on the Canadian Prairie Provinces. It is expected that the projected temperature variations would provide scientific bases for adaptation and mitigation initiatives on multiple sectors, such as agriculture and economic sectors.

2. Model Setup, Study Area, and Data Sets

In this study, physically-based climate downscaling is based on the 4.6.0 version of RegCM, which is developed by the International Center for Theoretical Physics [37–40]. The RegCM4.6 model is employed to dynamically downscale the GFDL-ESM2M simulations [41–44], which are derived from the historical (1950–2005) and future (2006–2099) experiments under RCPs [35]. Specifically, the intermediate (i.e., RCP4.5) and heavy (i.e., RCP8.5) emission scenarios are chosen to reveal the range of possible future climate variations. Such emission scenarios are mainly distinctive from each other after the year 2050. More specific information for the scenarios is illustrated in the previous studies [9,35].

The study area is within the context of the Canadian Prairie Provinces, which include the Provinces of Manitoba, Saskatchewan, and Alberta. As shown in Figure 1, the topography in the study area is varied and complicated. The highest and lowest elevation is 3434 and 1 m, respectively. The Prairie Provinces have a total surface area of over 1,960,000 km$^2$, accounting for 19.6% of the entire area of Canada [9]. Moreover, the climatic patterns of the Arctic and the Rocky Mountain have significant impacts on the climate of the Canadian Prairie Provinces [35,45].

A spatial experiment domain of 108 longitude \( \times \) 128 latitude grid points with a horizontal resolution of 0.22° \( \times \) 0.22° (i.e., approximately 25 km) is set up to cover the Prairie Provinces [9]. The land surface scheme is the 4.5 version of the Community Land Model (CLM4.5), while the multiple-phase cloud microphysics scheme is selected as the moisture scheme in RegCM4.6 [46]. The microphysics scheme is employed as the moisture scheme, while the lateral boundary condition scheme is the relaxation exponential
technique [47,48]. The Holtslag PBL [49] is chosen as the boundary layer scheme and the cumulus convective scheme is the Emanuel scheme [50].

The RegCM4.6 model is undertaken to dynamically downscale daily mean, maximum, and minimum temperature (expressed as $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$) over the Canadian Prairies. Annual averages of the daily temperatures for future periods of both 2036 to 2065 and 2066 to 2095 are calculated. The changes in temperature relative to the baseline period (i.e., 1985 to 2004) are then analyzed. Particularly, the changes in temperature (i.e., $V_{\text{mean}}$, $V_{\text{max}}$, and $V_{\text{min}}$) can be calculated as follows:

$$V_{\text{mean}} = T_{\text{mean}}^f - T_{\text{mean}}^h$$  \hspace{1cm} (1)

$$V_{\text{max}} = T_{\text{max}}^f - T_{\text{max}}^h$$  \hspace{1cm} (2)

$$V_{\text{min}} = T_{\text{min}}^f - T_{\text{min}}^h$$  \hspace{1cm} (3)

The annual average of daily maximum temperature over the Canadian Prairies in the period of 1960 to 2005 ranged from $-4.0$ to $12.6^\circ$C, whereas daily minimum temperature varied from $-12.2$ to $0.6^\circ$C. From 1960 to 2005, the maximum and minimum temperature increased by 1.5 and 2.3$^\circ$C, respectively. The spatial average of daily mean temperature for the period of 1960 to 2005 fluctuated from 3.7 to 7.3$^\circ$C, which increased by 1.6$^\circ$C since 1895 [9].

Intensified greenhouse-gas impacts and aggravated land-cover changes have contributed to increases in annual averages of daily maximum and minimum temperature [51]. It is expected that such increases would be amplified in the future, which can significantly affect the agriculture sector in the Canadian Prairies. Therefore, a higher spatial resolution of climate projections is needed to reveal the impacts of climate changes on the Canadian Prairies, and thus facilitate proper mitigative and adaptive strategies.

The historical climate observations over the Canadian Prairies were derived from a 10 km gridded climate dataset, which was produced by the National Land and Water Information Service (NLWIS), Agriculture and Agri-Food, Canada [52]. In this study, daily maximum and minimum temperatures in the period of 1985 to 2004 were extracted to analyze the annual averages within the study area. The elevation of the Canadian Prairie Provinces with a horizontal resolution of 30 arc-seconds was acquired from the Canadian Digital Elevation Data, which is developed by the Canadian Forestry Service, Ontario region [53].

The changes in temperature relative to the baseline period (i.e., 1895 to 2004) can be calculated as follows:
where $T_{\text{mean}}^f$, $T_{\text{max}}^f$, and $T_{\text{min}}^f$ represent the annual average of daily mean, maximum, and minimum temperature in the future periods, respectively; whereas $T_{\text{mean}}^h$, $T_{\text{max}}^h$, and $T_{\text{min}}^h$ indicate the annual average of daily mean, maximum, and minimum temperature for the historical period (i.e., 1985 to 2004). Detailed steps for projecting temperature variations through the RegCM4.6 model are summarized in Figure 2.

Figure 2. Methodological framework for projecting temperature variations.

3. Projected Variations of Temperature

Previous studies have illustrated that RCMs are capable of capturing regional terrestrial and atmospheric processes as compared with GCMs [9,35]. The performance of RCMs in reproducing the historical temperature observations has been evaluated in previous studies [9,35,45,54–60]. Therefore, the development of fine-resolution temperature projections is the focus of this study. To comprehensively reveal how future temperature would be changed over the Canadian Prairies, temperature variations (i.e., $V_{\text{mean}}$, $V_{\text{max}}$, and $V_{\text{min}}$) in two future periods of both 2036 to 2065 and 2066 to 2095 under RCPs are analyzed with respective to the baseline period of 1985 to 2004.

Figure 3 presents the projected variations of annual averages of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$ for the period of 2036 to 2065 under RCP45 relative to the baseline period. The figures in columns one and two show the spatial distribution of projected averages of daily temperatures for the historical and future period, respectively, whereas column three shows the calculated variations (i.e., $V_{\text{mean}}$, $V_{\text{max}}$, and $V_{\text{min}}$); rows one to three present $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$, respectively. For $T_{\text{mean}}$, the simulated spatial average and standard deviation
over the entire area for the historical period are −0.4 and 2.1 °C, respectively (Figure 3a). It can be found that there is a decreasing pattern of the annual average from north to south. The spatial distribution from the future experiment in the period of 2036 to 2065 under RCP4.5 (Figure 3b) is closed to the historical one (Figure 3a), with an obviously increased magnitude. The result also indicates that the spatial average of $T_{\text{mean}}$ over the provinces is projected to be 1.0 °C in the period of 2036 to 2065, where maximum and minimum values in the map reach −7.3 °C in the southwest and 5.8 °C in the southeast, respectively. However, a smaller standard deviation of 1.9 °C is projected for the period of 2036 to 2065, which indicates that the spatial variation would be reduced due to the increased magnitude of negative values under climate change. As shown in Figure 3c, the average of $T_{\text{mean}}$ increases over the entire of the Prairie Provinces, with a northeastward-intensified pattern of projected changes. In addition, the RegCM model also simulates the largest increase at 56.60° N and 96.73° W in the northeast of Manitoba, and the smallest one at 51.47° N and 112.66° W in the southwest of Alberta.

Compared with $T_{\text{mean}}$, most of the spatial averages of $T_{\text{max}}$ are generally simulated to be above zero degrees, with the magnitude varying from −5.7 to 8.2 °C. The results derived from the RegCM model also show that $T_{\text{max}}$ has a spatial average of 4.3 °C and a standard deviation of 2.1 °C over the entire area for the historical period of 1985 to 2004 (Figure 3d). For the projected average of $T_{\text{max}}$, generally the future (Figure 3e) and the historical (Figure 3d) experiments have a similar gradient pattern, but amplified values are revealed in the future period of 2036 to 2065. In particular, a spatial average of 5.6 °C over the Canadian Prairies is projected, with a standard deviation of 2.1 °C in the future period under RCP4.5. Figure 3f presents the projected variations of annual averages of $T_{\text{max}}$ for the future period relative to the baseline period. It can be observed that the entire Prairie Provinces would experience increases in $T_{\text{max}}$, with a gradient intensified pattern.
from southwest to northeast. Likewise, the spatial average of \( T_{\text{max}} \) would increase from 0.6 to 2.1 \(^\circ\)C, while the most significant increase is found at the grid of 58.13\(^\circ\)N and 94.91\(^\circ\)W in the northeastern part.

In contrast, \( T_{\text{min}} \) over the Prairie Provinces is almost below zero degrees, with a spatial average of \(-4.6\) \(^\circ\)C and a standard deviation of 2.4 \(^\circ\)C (Figure 3g). It also indicated that greater spatial variations are presented in \( T_{\text{min}} \) as compared with \( T_{\text{max}} \). The spatial pattern of both simulated historical and projected future average of \( T_{\text{min}} \) matches each other quite well (Figure 3g,h), but with much greater values. A spatial average of \(-3.1\) \(^\circ\)C over the Canadian Prairies is projected, with a standard deviation of 2.2 \(^\circ\)C in the period of 2036 to 2065 under RCP4.5. The greatest and smallest average are projected to be 3.4 \(^\circ\)C in the southeast and \(-11.0\) \(^\circ\)C in the Rocky Mountain area, respectively. However, smaller spatial variations in the future might be caused by increased values of negative \( T_{\text{min}} \) under climate change. The projected variations of annual averages of \( T_{\text{min}} \) for the future period are presented in Figure 3i. Similar to \( T_{\text{max}} \) during the future period, the annual averages of \( T_{\text{min}} \) increase from 0.8 to 2.3 \(^\circ\)C. It also can be observed that there is a gradient intensified pattern from southwest to northeast. Similarly, the most significant increase is located at 56.86\(^\circ\)N and 88.97\(^\circ\)W in the northeast, whereas the smallest one is at 51.47\(^\circ\)N and 112.66\(^\circ\)W in the southwest.

Moreover, Figure 4 depicts the annual averages of \( T_{\text{mean}}, T_{\text{max}}, \) and \( T_{\text{min}} \) for the period of 2066 to 2095 under RCP4.5, as well as their changes with respect to the baseline. Similarly, the spatial distributions of projected averages of daily temperatures for the historical and future period are shown in columns one and two, respectively. Column three depicts the computed changes in the projected values relative to the baseline period. In addition, the \( T_{\text{mean}}, T_{\text{max}}, \) and \( T_{\text{min}} \) respectively are presented in rows one to three. In general, there is a similar spatial distribution pattern of projected variations among \( T_{\text{mean}}, T_{\text{max}}, \) and \( T_{\text{min}} \) for the historical and future period. Similar to the revelations during the period of 2036 to 2065, the spatial average of \( T_{\text{mean}}, T_{\text{max}}, \) and \( T_{\text{min}} \) for the period of 2066 to 2095 increase by 1.7, 1.6, and 1.8 \(^\circ\)C, respectively (Figure 4c,f,i). However, such increases are projected as slightly greater than those in the period 2036 to 2065 under RCP4.5. Moreover, the projected changes in the annual averages of \( T_{\text{mean}}, T_{\text{max}}, \) and \( T_{\text{min}} \) would be amplified from the southwest in the Rocky Mountain area to the northeast in the prairie region.

In order to further analyze the projected variations of \( T_{\text{mean}}, T_{\text{max}}, \) and \( T_{\text{min}} \), the spatial distributions of their annual averages over the entire domain for the period of 2036 to 2065 and 2066 to 2095 under RCP4.5 are compared to those for the baseline period (Figure 5). In general, the shape of the distribution of \( T_{\text{mean}}, T_{\text{max}}, \) and \( T_{\text{min}} \) among three different periods matches each other. However, intensification of daily temperatures in the future is evident as shown from the changes of mean values, which is consistent with the previous revelations (Figures 3 and 4). It can be observed that there is no significant difference in the projected changes between the period of 2036 to 2065 and the period of 2066 to 2095 in terms of the mean and standard deviation. For example, the mean and standard deviation of projections for \( T_{\text{min}} \) in the period of 2036 to 2065 are projected to be \(-2.8\) and \(2.3\) \(^\circ\)C, respectively. Nevertheless, during the period of 2066 to 2095, the mean of projections is \(-3.1\) \(^\circ\)C with a standard deviation of 2.2 \(^\circ\)C.

Figure 6 displays the projected annual averages of \( T_{\text{mean}}, T_{\text{max}}, \) and \( T_{\text{min}} \) for the period of 2036 to 2065 under RCP8.5. In the same way, the figures in columns one to three respectively present the simulated averages of daily temperatures for the historical and future periods, as well as their differences. The figures in rows one to three show \( T_{\text{mean}}, T_{\text{max}}, \) and \( T_{\text{min}} \), respectively. Overall, the results show that the projections in the period of 2036 to 2065 under RCP8.5 are similar to those under RCP4.5. Moreover, there is an apparent warming pattern during the period of 2036 to 2065 under RCP8.5. For example, the RegCM model simulates the spatial averages of \(-4.6\) and \(-2.5\) \(^\circ\)C for \( T_{\text{min}} \) during the period 1985 to 2004 and 2036 to 2065, respectively. The largest average over the map during the future period of 2036 to 2065 is located at 50.20\(^\circ\)N and 98.04\(^\circ\)W in the southeast, nevertheless, the smallest one is at 52.19\(^\circ\)N and 117.24\(^\circ\)W in the southwest (Figure 6b).
Moreover, significant increases under RCP8.5 are observed in the calculated differences between two periods. There is a similar intensified pattern from southwest to northeast, which is consistent with the results under RCP4.5.

To further analyze the temperature changes, Figure 7 presents the projected averages of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$ for the period of 2066 to 2095 under RCP8.5. Similar to the pattern during the period of 2036 to 2065 under RCP8.5, the increase in the averages would be reduced from the northeastern Prairie to the southeastern Rocky Mountain. However, it can be found that the projected increases during the period of 2066 to 2095 under RCP4.5 and RCP8.5 are significantly different from each other. For example, the maximum increases in annual averages of daily maximum temperature during the period of 2066 to 2095 under RCP4.5 and RCP8.5 are 2.5 and 4.5 °C, respectively. Such increases are amplified under RCP8.5 as caused by heavy GHG emissions.

The spatial distribution of annual averages over the entire Prairie Provinces for two future periods under RCP8.5 are in comparison with those for the baseline period (Figure 8). It is indicated that the distribution of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$ generally maintain the same shape among three different periods. Such revelations are also consistent with the results under RCP4.5. Nevertheless, the projected averages of daily temperatures are significantly intensified as seen from the shifted mean values. For example, the mean value of $T_{\text{max}}$ in the period of 2066 to 2095 is projected to be 6.0 °C under RCP4.5, whereas it is enlarged to 7.8 °C under RCP8.5.
Figure 5. Spatial distribution of annual averages for the historical and future periods under RCP45. (a) $T_{\text{mean}}$, (b) $T_{\text{max}}$, and (c) $T_{\text{min}}$.

Figure 6. Projected variations of annual averages of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$ for the period of 2036 to 2065 under RCP85. (a,d,g) show the historical distributions of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$, respectively; (b,e,h) show the future distributions of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$, respectively; (c,f,i) show the projected variations of $V_{\text{mean}}$, $V_{\text{max}}$, and $V_{\text{min}}$, respectively.
Figure 7. Projected variations of annual averages of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$ for the period of 2066 to 2095 under RCP8.5. (a,d,g) show the historical distributions of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$, respectively; (b,e,h) show the future distributions of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$, respectively; (c,f,i) show the projected variations of $V_{\text{mean}}$, $V_{\text{max}}$, and $V_{\text{min}}$, respectively.

Figure 8. Spatial distribution of annual averages for the historical and future periods under RCP85. (a) $T_{\text{mean}}$, (b) $T_{\text{max}}$, and (c) $T_{\text{min}}$. In order to further explore the impacts of climate change on the Prairie Provinces, the Mann–Kendall (MK) test [61,62] and the non-parametric Theil–Sen (TS) estimator [63,64] were performed to reveal the temporal trends in annual averages of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$ at multiple stations under RCPs. In this study, sixteen spatially distributed stations are chosen, while more details can be referred to in Zhou et al. [9]. The probability of the MK test statistics and the magnitude of the TS estimator are examined for demonstrating how the Prairie Provinces are affected within the context of global warming.

Figure 9 shows the time series and temporal trends of annual averages of $T_{\text{mean}}$ at the 16 stations for two future periods under RCPs. It can be observed that the $p$-values of the MK test statistics at the majority of stations for future periods under RCP8.5 are less than the significance level ($\alpha = 0.05$), indicating that there are significant trends in the annual averages of $T_{\text{mean}}$. Particularly, $T_{\text{mean}}$ at all the stations in the period of 2066 to 2095 under RCP4.5 shows insignificant trends, ranging from $-0.029$ to $0.020$ °C/year. This might be attributable to the stabilization of the population growth, land-use conversions, and greenhouse gas (GHG) emissions under RCP4.5 after the year 2050.
4. Projected Trends of Temperature

In order to further explore the impacts of climate change on the Prairie Provinces, the Mann–Kendall (MK) test \([61,62]\) and the non-parametric Theil–Sen (TS) estimator \([63,64]\) were performed to reveal the temporal trends in annual averages of \(T_{\text{mean}}\), \(T_{\text{max}}\), and \(T_{\text{min}}\) at multiple stations under RCPs. In this study, sixteen spatially distributed stations are chosen, while more details can be referred to in Zhou et al. \([9]\). The probability of the MK test statistics and the magnitude of the TS estimator are examined for demonstrating how the Prairie Provinces are affected within the context of global warming.

Figure 9 shows the time series and temporal trends of annual averages of \(T_{\text{mean}}\) at the 16 stations for two future periods under RCPs. It can be observed that the \(p\)-values of the MK test statistics at the majority of stations for future periods under RCP8.5 are less than the significance level \((\alpha = 0.05)\), indicating that there are significant trends in the annual averages of \(T_{\text{mean}}\). Particularly, \(T_{\text{mean}}\) at all the stations in the period of 2066 to 2095 under RCP4.5 shows insignificant trends, ranging from \(-0.029\) to \(0.020\) \(^{\circ}\)C/year. This might be attributable to the stabilization of the population growth, land-use conversions, and greenhouse gas (GHG) emissions under RCP4.5 after the year 2050.

![Figure 9: Temporal trends in annual averages of \(T_{\text{mean}}\) at the 16 stations.](image-url)

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**Figure 9.** Temporal trends in annual averages of \(T_{\text{mean}}\) at the 16 stations. The value of \(p\) and trend is derived from the MK test and the Theil–Sen estimator, respectively. The straight line represents the linear trend derived from the Theil–Sen estimator. (a) Edmonton, (b) Calgary, (c) Fort Mcmurray, (d) Red Deer, (e) Medicine Hat, (f) Grande Prairie, (g) Key Lake, (h) Saskatoon, (i) Regina, (j) Waseca, (k) Pelly, (l) Winnipeg, (m) Gillam, (n) Thompson, (o) Brandon, and (p) The Pas.
In addition, temporal trends are investigated for annual averages of $T_{\text{max}}$ and $T_{\text{min}}$ for future periods under RCPs, which are presented in Figures 10 and 11, respectively. It can be noticed that similar warming trends are detected for the annual averages at all the stations under RCP8.5. However, the magnitude of positive trends in $T_{\text{mean}}$ for most stations is generally smaller than $T_{\text{min}}$, while larger than $T_{\text{max}}$. This is also consistent with the results of projected variations, where larger increases are reported in $T_{\text{min}}$. It is also evident that the trends in $T_{\text{max}}$ and $T_{\text{min}}$ at all the stations in the period of 2066 to 2095 under RCP4.5 are insignificant, as seen from the $p$-values of the MK test statistics.

Figure 10. Temporal trends in annual averages of $T_{\text{max}}$ at the 16 stations. The value of $p$ and trend is derived from the MK test and the Theil–Sen estimator, respectively. The straight line represents the linear trend derived from the Theil–Sen estimator. (a) Edmonton, (b) Calgary, (c) Fort McMurray, (d) Red Deer, (e) Medicine Hat, (f) Grande Prairie, (g) Key Lake, (h) Saskatoon, (i) Regina, (j) Waseca, (k) Pelly, (l) Winnipeg, (m) Gillam, (n) Thompson, (o) Brandon, and (p) The Pas.
Figure 11. Temporal trends in annual averages of $T_{\text{min}}$ at the 16 stations. The value of $p$ and trend is derived from the MK test and the Theil–Sen estimator, respectively. The straight line represents the linear trend derived from the Theil–Sen estimator. (a) Edmonton, (b) Calgary, (c) Fort Mcmurray, (d) Red Deer, (e) Medicine Hat, (f) Grande Prairie, (g) Key Lake, (h) Saskatoon, (i) Regina, (j) Waseca, (k) Pelly, (l) Winnipeg, (m) Gillam, (n) Thompson, (o) Brandon, and (p) The Pas.

5. Discussion

In this study, the Canadian Prairies shows a larger increase in the annual averages of $T_{\text{min}}$ than those of $T_{\text{max}}$ (Figure 12). This also implies that projected increases in annual averages of $T_{\text{max}}$ (Figure 12b) make a smaller contribution than $T_{\text{min}}$ (Figure 12c) to the increase in annual averages of $T_{\text{mean}}$ (Figure 12a). The downscaling experiments also reveal that the trends in $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$ at all the stations in the 2080s under RCP4.5 are insignificant. This might be attributable to the stabilization of population growth, land-use conversions, and greenhouse gas (GHG) emissions under RCP4.5 after the year 2050. Moreover, we found that greater increases in annual averages of daily temperatures are projected under RCP8.5 than those under RCP4.5, indicating that a higher emission scenario will initiate a more significant increase in temperatures due to greenhouse gas effects.

The projected results of temperature variations reveal that increases in the annual averages of daily temperatures would be intensified from the southwest in the Rocky Mountain area to the northeast in the prairie region. This is most likely due to the dynamic effects of a strong positive ice-snow albedo feedback, amplifying climate change as a result of decreasing ice-snow cover in the prairie region. The contribution of ice-snow albedo feedback to larger increases in the annual averages of $T_{\text{min}}$ in the northeast region would be more significant than $T_{\text{max}}$ due to a similar amplification effect. This is also consistent
with the previous studies, which indicate that the high-latitude ice-snow albedo feedback is a primary element in projected increases in temperatures under the global warming scenarios [65–67].

Figure 12. Spatial averages of projected changes for the future periods under RCPs. (a) $T_{\text{mean}}$, (b) $T_{\text{max}}$, and (c) $T_{\text{min}}$.

6. Conclusions

In this study, dynamically downscaled variations of daily mean, maximum, and minimum temperature over the Canadian Prairies were developed through regional climate simulations. How the regional climate will increase in response to global warming in the future was thus analyzed. Specifically, RegCM was undertaken to downscale the boundary conditions of GFDL-ESM2M. Daily temperatures were subsequently extracted from the historical and future simulations. Temperature variations in the future periods (i.e., 2036 to 2065 and 2065 to 2095) are then investigated relative to the baseline period (i.e., 1985 to 2004). The spatial temperature distributions were analyzed to reveal the regional impacts of global warming on the Prairie Provinces.

The results suggested that the spatial distribution from the future experiment in the period of 2036 to 2065 under RCP4.5 is closed to the historical one, with an obviously increased magnitude. Moreover, it could be observed that there is no significant difference in the projected changes in temperatures between the period of 2036 to 2065 and the period of 2066 to 2095 in terms of their mean and standard deviation. The results further indicated that the projected changes would be amplified from the southwest in the Rocky Mountain area to the northeast in the prairie region. It was also suggested that the projected changes would be significantly intensified under RCP8.5. The projected variations of daily mean, minimum, and maximum temperature could provide scientific bases for adaptation and mitigation initiatives on multiple sectors, such as agriculture and economic sectors.

Significant increases in temperatures over the Canadian Prairies have been revealed through a comprehensive analysis of the projected variations. Such revealed increases can provide scientific bases for identifying appropriate adaptation and mitigation initiatives on multiple sectors. This study is limited since the RegCM model is merely driven by one GCM, which has difficulty in reflecting the uncertainties of boundary conditions. However, such boundary data provided by GCM outputs could significantly affect the projected temperature variations. Therefore, future research efforts can be extended to investigate...
the full potential ranges of temperature increases through dynamical downscaling of multiple GCMs.

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