Clim Dyn (2018) 50:1321–1334
DOI 10.1007/s00382-017-3687-9

Dynamically-downscaled temperature and precipitation changes over Saskatchewan using the PRECIS model

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Received: 21 September 2016 / Accepted: 11 April 2017 / Published online: 20 April 2017

Abstract In this study, dynamically-downscaled temperature and precipitation changes over Saskatchewan are developed through the Providing Regional Climates for Impacts Studies (PRECIS) model. It can resolve detailed features within GCM grids such as topography, clouds, and land use in Saskatchewan. The PRECIS model is employed to carry out ensemble simulations for projections of temperature and precipitation changes over Saskatchewan. Temperature and precipitation variables at 14 weather stations for the baseline period are first extracted from each model run. Ranges of simulated temperature and precipitation variables are then obtained through combination of maximum and minimum values calculated from the five ensemble runs. The performance of PRECIS ensemble simulations can be evaluated through checking if observations of current temperature at each weather station are within the simulated range. Future climate projections are analyzed over three time slices (i.e., the 2030s, 2050s, and 2080s) to help understand the plausible changes in temperature and precipitation over Saskatchewan in response to global warming. The evaluation results show that the PRECIS ensemble simulations perform very well in terms of capturing the spatial patterns of temperature and precipitation variables. The results of future climate projections over three time slices indicate that there will be an obvious warming trend from the 2030s, to the 2050s, and the 2080s over Saskatchewan. The projected changes of mean temperature over the whole Saskatchewan area is [0, 2] °C in the 2030s at 10th percentile, [2, 5.5] °C in the 2050s at 50th percentile, and [3, 10] °C in the 2090s at 90th percentile. There are no significant changes in the spatial patterns of the projected total precipitation from the 2030s to the end of this century. The minimum change of the projected total precipitation over the whole Province of Saskatchewan is most likely to be −1.3% in the 2030s, and −0.2% in the 2050s, while the minimum value would be −2.1% to the end of this century at 50th percentile.

Keywords Global warming · Regional climate modeling · Climate change · Saskatchewan

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1 Introduction

The challenge of climate change has been one of the most important and urgent environmental concerns to many researchers and managers in recent decades. Global climate models (GCMs) are widely used to project future climate under the Special Report on Emissions Scenarios (Nakicenovic et al. 2000) or the representative concentration pathways (Van Vuuren et al. 2011). However, GCMs are unable to represent more details of local processes, coastlines, land use, and topography, which may contribute to the simulation of meaningful small-scale features over limited regions at affordable costs (Denis et al. 2002; Jones et al. 1995). Further downscaling is thus desired to obtain regional climate details from the coarse-resolution outputs for climate change impacts assessments (IPCC 2013; Maurer et al. 2007; Quintana-Seguí et al. 2016; Wang et al. 2015a).

As one of the prairie provinces in Canada, the Province of Saskatchewan is now suffering more frequent and severe extremes due to the climate change, such as winter temperatures below −50 °C and summer temperatures above 40 °C, as well as extensive drought and flooding. Such extremes will have significant impacts on the environment and economy over the Province of Saskatchewan (Natural Resources Canada 2015). In order to manage climate change issues, the Government of Saskatchewan is developing workable strategies such as development of both carbon capture and storage (CCS) and renewable energy technologies (Saskatchewan Ministry of the Environment 2013). However, adapting to climate changes requires better understanding of how the climate will change in both short and long term in the context of Saskatchewan. Therefore, high-resolution regional climate projections over the Province of Saskatchewan are required for improving mitigation and adaptation strategies against climate change.

In the past decades, a large number of statistical downscaling methods have been employed to generate high-resolution regional climate projections and assess climate change impacts (Chen et al. 2014; Jacobeit et al. 2014; Maraun et al. 2015; Sachindra et al. 2014). In general, the approaches for statistical downscaling mainly involve the establishment of quantitative relationships between large-scale atmospheric variables and station surface variables (He et al. 2016; Gong et al. 2016; Tong et al. 2016; Wang et al. 2015b). Due to their low computation requirements, the statistical downscaling methods were widely employed in various climate-related studies (Wang et al. 2015b; Wilby et al. 2004). However, statistical downscaling is based on an unverifiable assumption that the statistical relationships should be stationary under different future climate forcing conditions (Vincent and Gullett 1999; Wilby et al. 2004). Nevertheless, as a typical dynamical downscaling approach, regional climate models (RCMs) are consistent with physical mechanisms in global climate models (GCMs) to physically resolve more detailed features within GCM grids such as mountain ranges, coastal zones, and details of soil properties (Feser et al. 2011).Through nesting RCMs into GCMs, it can develop the improved simulation of GCMs and thus can generate projections for temperature and precipitation variables at finer spatial scales (Lavender and Walsh 2011; Wang et al. 2015b; White et al. 2013). However, there has not been any report of high-resolution dynamic downscaling of temperature and precipitation changes over Saskatchewan, Canada.

Therefore, the objective of this study is to develop high-resolution regional climate projections over the Province of Saskatchewan using the Providing Regional Climates for Impacts Studies (PRECIS) model. PRECIS will be employed to carry out ensemble simulations for the current and future climate over Saskatchewan. The performance of PRECIS ensemble simulations in reproducing historical climatology of Saskatchewan will be first evaluated through comparing with the observed temperature and precipitation. Future climate projections throughout the twenty-first century will then be analyzed over three time slices (i.e., the 2030s, 2050s, and 2080s) to help understand the plausible changes in temperature and precipitation over Saskatchewan in response to global warming. It is expected that changes of climatic conditions in Saskatchewan will be revealed in the upcoming decades. The developed ensemble projections can provide decision makers with valuable information for climate change impact assessment over Saskatchewan.

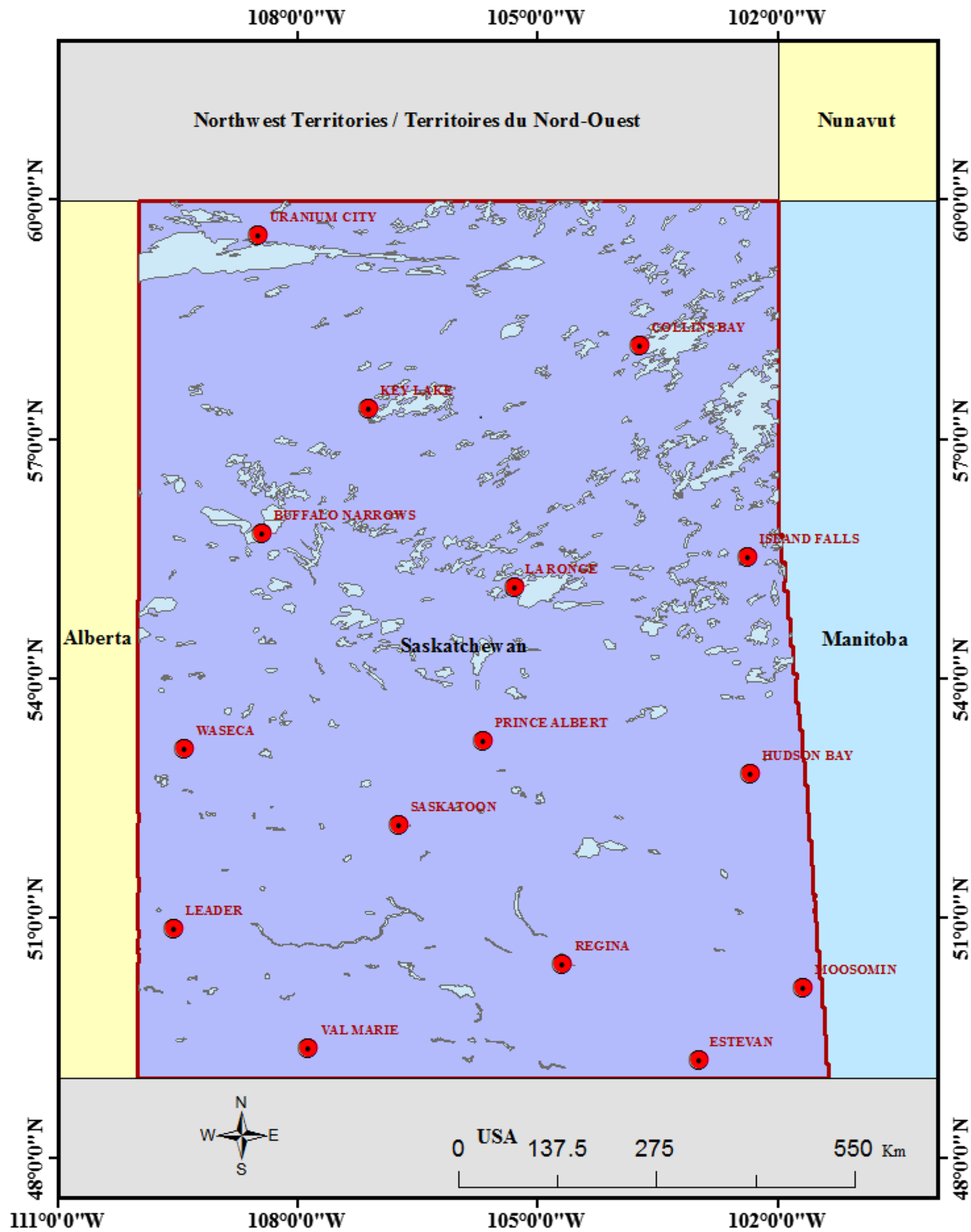
2 Data and methods

2.1 Study area

As shown in Fig. 1, the Province of Saskatchewan is one of the prairie provinces (i.e., Saskatchewan, Manitoba, and Alberta) in Canada, bordered by the Province of Alberta to the west, and the Northwest Territories to the north, the Province of Manitoba to the east, and the US states of Montana and North Dakota to the south. It has a total area of 651,036 km^2 and an abundance of energy resources (Statistics Canada 2005; Zhou et al. 2015a). The current population of Saskatchewan is 1.134 million, approximately 3.6% of Canadian population (Statistics Canada 2014). Saskatchewan is mostly dry with short-hot summers and long-cold winters, as well as low precipitation with high evaporation (deJong et al. 2010). For example, the annual precipitation over Saskatchewan varies from 250 mm in the dry grasslands to over 500 mm in the humid regions (deJong et al. 2010). Temperatures in Saskatchewan can rise above 40 °C during summer, whereas can fall below −50 °C during winter. The annual average temperatures throughout Saskatchewan has warmed with approximately 1 °C during the twentieth Century (Saskatchewan Eco Network 2009). The increased temperature, which was mainly observed in the winter and spring, may affect agriculture and forestry, as evidenced by the costs associated with recent drought and forest fires (Saskatchewan Eco Network 2009). Moreover, there are reductions in both the availability of water and quality of soil in Saskatchewan due to climate change and human activities (deJong et al. 2010; Schindler and Donahue 2006; Zhou et al. 2015b). The largest effect of climate change in Saskatchewan to date has been caused by extreme rainfall and extensive flooding events (Saskatchewan Environmental Society 2016).

In response to climate change, the Government of Saskatchewan has been working on reducing its GHG emissions, which has prioritized cleaning up its coal generation

Fig. 1 Map of the study area



through introducing carbon capture and storage technology (Saskatchewan Ministry of the Environment 2013). The legislative and regulatory tools will also be developed to help identify and achieve provincial targets of GHG reduction for limiting climate-related increases in temperature in Saskatchewan (Saskatchewan Ministry of the Environment 2013). Therefore, a regional climate modeling approach is desired for a better understanding of how the climate of Saskatchewan will change in both short and long term.

2.2 Observations of current climate

To conduct undermentioned validation analysis, the observation data for monthly mean of daily maximum temperature, daily minimum temperature, daily mean temperature, and monthly total of daily adjusted total precipitation are obtained from the Adjusted and Homogenized Canadian Climate Data (AHCCD) by Environment and Climate Change Canada (Environment and Climate Change Canada 2013). Due to changes in observing practices and automation, as well as the relocation of the weather stations, non-climatic shifts were existed in the annual means of the daily maximum and minimum temperatures (Environment and Climate Change Canada 2013; Vincent and Gullett 1999). Adjustments (e.g., combination of observations from nearby stations) were applied to monthly and daily maximum and minimum temperatures to create long time series (Environment and Climate

Table 1 14 weather stations selected in Saskatchewan

No.	Weather station	Latitude	Longitude	Abbreviation
01	Buffalo Narrows	55.8°N	108.4°W	BN
02	Collins Bay	58.2°N	103.7°W	CB
03	Estevan	49.2°N	103.0°W	EV
04	Hudson Bay	52.9°N	102.6°W	HB
05	Island Falls	55.5°N	102.4°W	IF
06	Key Lake	57.3°N	105.6°W	KL
07	Leader	55.2°N	105.3°W	LR
08	Moosomin	50.1°N	101.7°W	MM
09	Prince Albert	53.2°N	105.7°W	PA
10	Regina	50.4°N	104.7°W	RA
11	Saskatoon	52.2°N	106.7°W	ST
12	Uranium City	59.6°N	108.5°W	UC
13	Val-Marie	49.4°N	107.8°W	VM
14	Waseca	53.1°N	109.4°W	WA

Change Canada 2013; Vincent and Gullett 1999; Vincent et al. 2002). In this study, 14 weather stations are selected, which are spatially distributed across Saskatchewan (Fig. 1; Table 1). The data for 1961–1990 at these stations is extracted to represent the observations of historical climate in the context of Saskatchewan.

2.3 Regional climate modeling

In this study, the PRECIS regional climate modeling system developed by the UK Hadley Centre is applied to develop high-resolution climate projections for the Province of Saskatchewan. The PRECIS system is a hydrostatic and primitive equation grid-point model, comprising 19 levels described by a hybrid vertical coordinate (a combination of σ-coordinate and pressure coordinate) (Wilson et al. 2005; Wang et al. 2015c). The convective scheme is the mass flux penetrative scheme with an explicit downdraught (Gregory and Rowntree 1990), while the Met Office Surface Exchange Scheme is employed as the land surface model component (Cox et al. 1999). The radiation scheme includes the seasonal and diurnal cycles of insolation, computing short wave and long wave fluxes (Jones et al. 2004). The detailed model parameterization is described by Jones et al. (2004). It can be run over any area of the globe to provide detailed regional climate change projections for impacts studies (Jones et al. (2004; Wang et al. 2015c). There are two different horizontal resolutions: 0.44° × 0.44° and 0.22° × 0.22°, which respectively provide a minimum resolution of 50 km × 50 km and 25 km × 25 km at the equator of the rotated grid (Centella-Artola et al. 2015; Wang et al. 2014).

The PRECIS system can be driven by boundary data from a HadCM3-based perturbed physics ensemble, which is known as quantifying uncertainty in model predictions (QUMP) by using SRES A1B scenario (Bellprat et al. 2012; Wang et al. 2014). Such a capacity will be able to help explore the model uncertainty in regional climate change projections in Saskatchewan (Bellprat et al. 2012; Wang et al. 2014). The A1B scenario is selected in this study because it is a mid-range scenario that has been widely employed in climate change impact studies (Schaefer et al. 2011). The QUMP ensemble comprise 17 members referred as HadCM3Q0-16, which developed by the Met Office Hadley Centre (McSweeney and Jones 2010; Wang et al. 2015c). The QUMP ensemble is used here to drive the PRECIS model to generate an ensemble of high resolution projections of future climate change over Saskatchewan. However, large inputs of computing resources, data storage, and data analyses will be required to fully downscale the QUMP ensemble (McSweeney and Jones 2010; Wang et al. 2015c). Therefore, in this study, HadCM3Q0 is first selected since it is the standard and unperturbed model with original parameter settings (Wang et al. 2015c). The remaining four QUMP members are selected on the basis of (1) performances to simulate key features of the climate over Saskatchewan, and (2) ability to sample the range of outcomes of future changes simulated by the full 17-member ensemble (Bellprat et al. 2012; Wang et al. 2015c).

Outputs from the PRECIS ensemble simulations are extracted and splited into four 30 year periods, including 1961–1990 (the baseline period), 2020–2049 (the 2030s), 2040–2069 (the 2050s), and 2070–2099 (the 2080s). In order to evaluate the performance of ensemble simulations in reproducing the current climatology in the context of Saskatchewan, temperature and precipitation variables (i.e., T_{max}, T_{mean}, T_{min}, and Total precipitation) at 14 weather stations for the baseline period are first extracted from each model run. Ranges of simulated temperature and precipitation variables are then obtained through combination of maximum and minimum values, which are calculated from the five ensemble runs. Thus, the performance of PRECIS ensemble simulations can be validated through checking if observations of current temperature at each weather station are within the simulated range.

3 Results and discussion

3.1 Evaluation of the PRECIS simulations

The validation results at the selected weather stations for temperature and precipitation variables are provided in Fig. 2. It shows the biases between the ensemble simulations and observations for the 14 weather stations. For each temperature and precipitation variable, the minimum and maximum of the PRECIS ensemble simulations

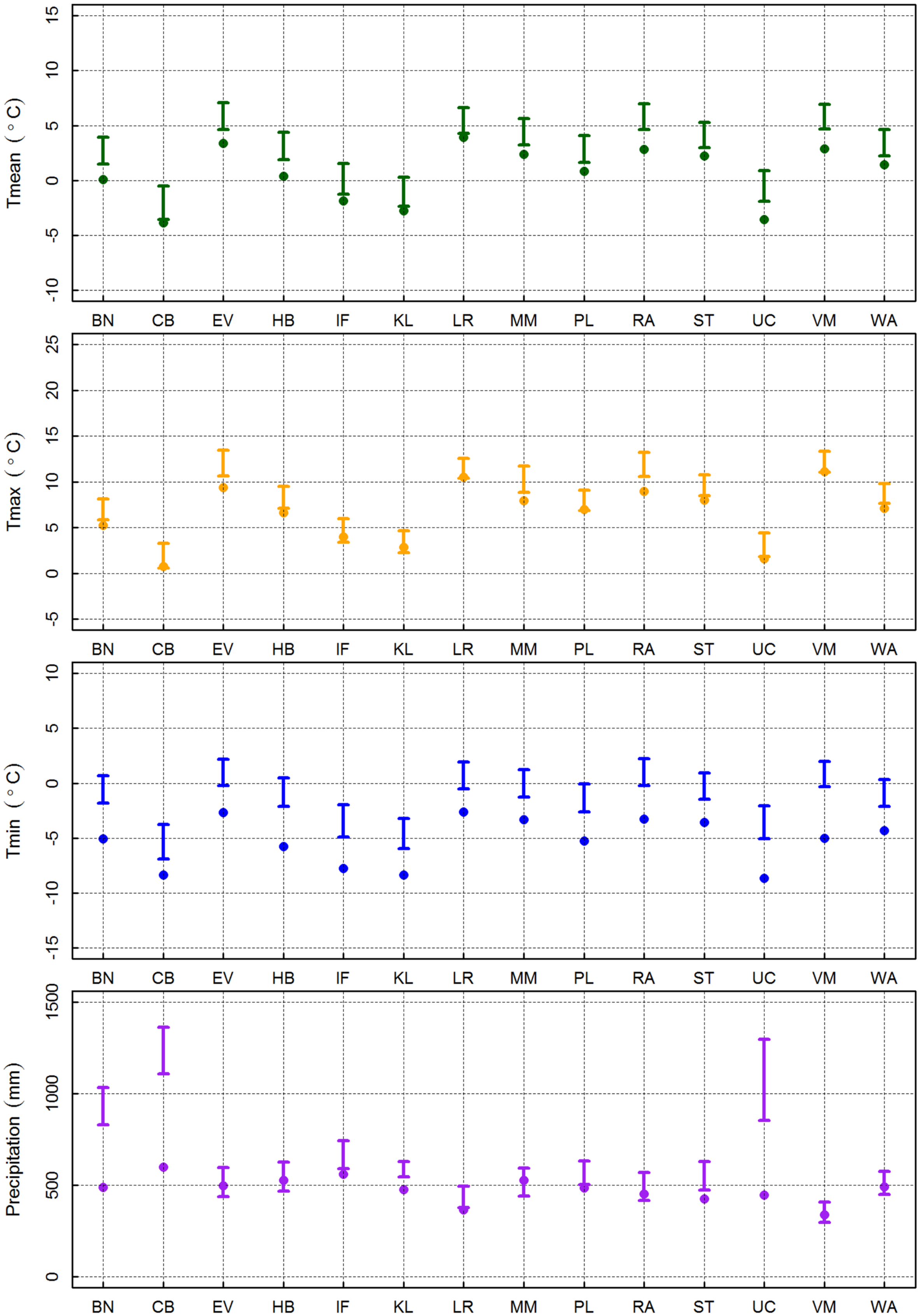


Fig. 2 Validation results at the major cities. The observed temperature means and total precipitation are displayed as round points, and the range bounded by the maximum and minimum of the ensemble simulations is indicated by the linear bar

are calculated. In detail, the observed means for T_{max} at selected weather stations are well captured by the ensemble simulations, except for slight warm biases by 0.3–1.6 °C at the 8 weather stations (i.e., Cities of Buffalo Narrows, Estevan, Hudson Bay, Moosomin, Regina, Saskatoon, Uranium City, and Waseca). It is indicated that the PRECIS ensemble simulations can be effective tools in terms of reproducing the observed means for T_{max} at the 14 weather stations in Saskatchewan.

Similarly, it can be found that the results also demonstrate outstanding performance in terms of reproducing observed T_{mean} at the 14 weather stations. The biases of T_{mean} for the 14 weather stations range from 0.3 °C (i.e., the City of Collins Bay) to 1.8 °C (i.e., the City of Uranium), which means that the observed T_{mean} at the selected stations are closed to the range bounded by the minimum and maximum of the PRECIS simulations. As for the results of T_{min}, the calculated biases are varying from 1.5 to 4.7 °C, implying that the PRECIS ensemble simulations tend to slightly overestimate the observed T_{min} at most of the weather stations. Although the ensemble simulations result in substantial warm bias relative to the observations at stations, the overall spatial patterns of T_{min} at the 14 weather stations are still well captured.

However, the performance of ensemble simulations in reproducing the observed means for total precipitation is not as effective as that for T_{mean}, T_{min}, and T_{max}. The calculated biases are varying from 0 mm (i.e., Cities of Estevan, Hudson Bay, Moosomin, Regina, Val-Marie, and Waseca) to 510.0 mm (i.e., the City of Collins Bay). Moreover, the results also indicate that there are large biases in simulated total precipitation for Buffalo Narrows (i.e., 340.7 mm), Collins Bay (i.e., 510.0 mm), and Uranium Cites (i.e., 405.8 mm). This is mainly because precipitation is more difficult to simulate than temperature due to its nonlinear nature and spatial variability (Maraun et al. 2010; Wang et al. 2015b).

3.2 Projections of future temperature and precipitation

Projections of future temperature and precipitation over Saskatchewan are developed using a high resolution regional climate model. In order to further analyze near-term, medium-term, and long-term spatial patterns of temperature and precipitation over the entire province of Saskatchewan, the projections for this century are thus divided into three 30 year periods: the 2030s (2020–2049), the 2050s (2040–2069), and the 2080s (2070–2099). The annual averages of one precipitation variable (i.e., total precipitation) and three temperature variables (i.e., T_{max}, T_{mean}, and T_{min}) are calculated for each 30 year period to represent the regional climatological features corresponding to the period. According to the approach used in the UK Climate Projections report (Murphy et al. 2009), the changes of the precipitation and temperature variables at three percentiles (i.e., 10th, 50th, and 90th) are calculated to provide a better understanding of possible future features. In detail, the value at 50th percentile is defined as the central estimate of future projections, which indicates that half of the simulation runs are less than or equal to it; and the interval bounded by values at 10th and 90th percentiles is defined as the mostly likely range within which the estimate of future projection will fall. The projections of precipitation and temperature variables at 14 weather stations will be analyzed. Moreover, the maps of the projected

Table 2 Projected T_{mean}, T_{max}, T_{min}, and total precipitation for the 14 weather stations at 50th percentile

Weather stations	T_{mean} (°C, 50th)			T_{max} (°C, 50th)			T_{min} (°C, 50th)			Precipitation (mm, 50th)		
	2030s	2050s	2080s	2030s	2050s	2080s	2030s	2050s	2080s	2030s	2050s	2080s
BN	3.9	5.8	7.3	8.1	9.9	11.4	0.7	2.6	4.1	822.9	853.2	848.1
CB	−1.6	0.3	1.8	1.8	3.6	5.0	−4.5	−2.5	−0.9	848.1	880.2	898.2
EV	8.3	10.4	12.5	14.2	16.4	18.0	3.4	5.5	7.4	590.8	592.9	577.6
HB	5.6	7.9	9.8	10.7	13.0	14.8	1.6	3.9	5.7	606.1	565.8	582.3
IF	2.6	4.9	6.8	7.3	9.6	11.4	−1.0	1.2	3.1	689.0	693.6	673.4
KL	1.3	3.4	5.2	5.9	7.9	9.7	−2.3	−0.2	1.6	612.9	599.5	624.9
LR	−0.5	0.8	1.8	2.2	3.4	4.3	−2.9	−1.6	−0.5	633.7	639.9	687.4
MM	6.8	9.1	11.2	12.3	14.7	16.3	2.4	4.6	6.5	587.2	587.5	564.2
PA	5.4	7.7	9.4	10.6	12.9	14.6	1.2	3.4	5.0	591.8	603.0	596.6
RA	8.3	10.5	12.5	14.3	16.4	18.0	3.5	5.6	7.4	549.7	524.9	530.0
ST	6.7	8.8	10.6	12.2	14.4	16.0	2.2	4.3	5.9	570.2	568.3	575.2
UC	1.4	3.4	5.2	5.1	7.1	8.7	−1.7	0.4	2.2	1031.6	1114.7	1092.7
VM	8.1	10.1	11.9	14.4	16.4	17.9	3.1	5.1	6.7	420.7	407.4	413.7
WA	6.1	8.1	9.8	11.6	13.6	15.3	1.6	3.5	5.1	519.3	557.3	560.2

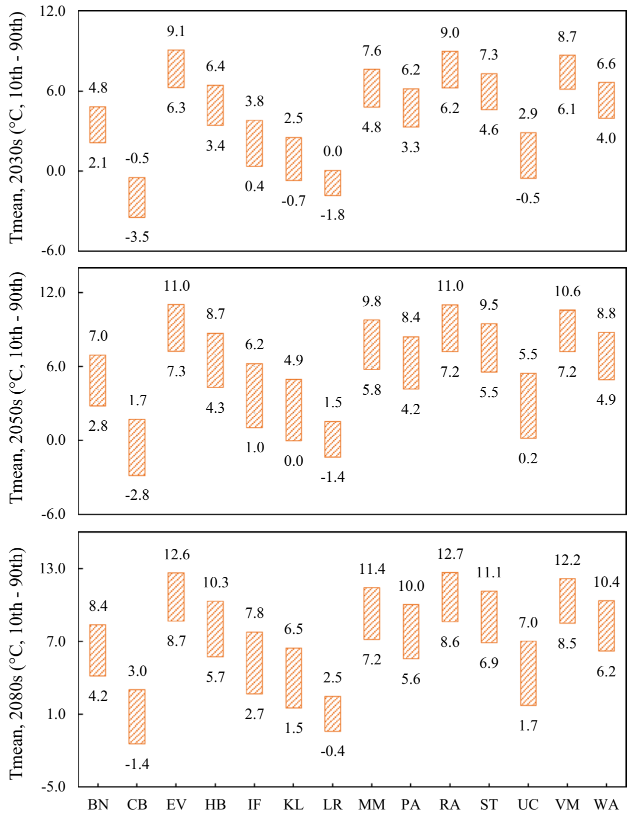


Fig. 3 Projected intervals of T_{mean} at the 14 weather stations

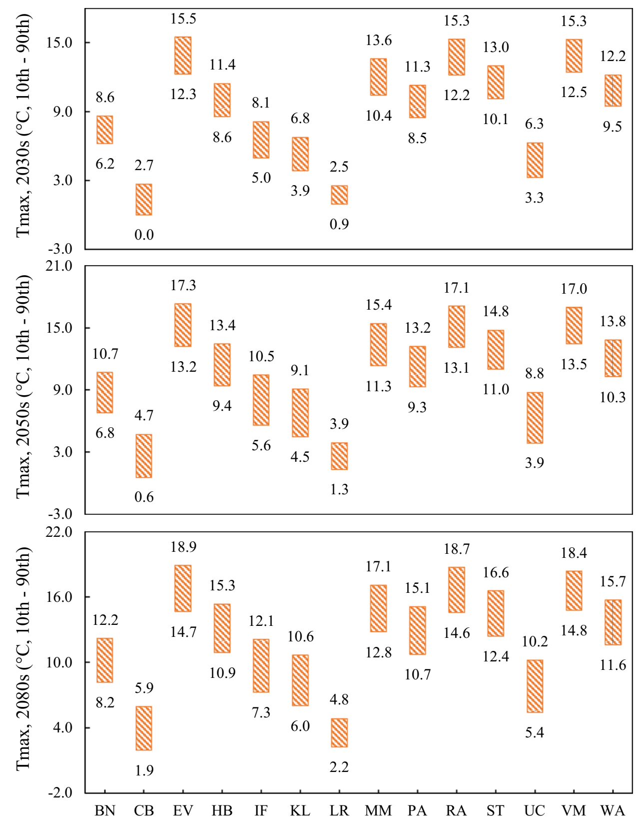


Fig. 4 Projected intervals of T_{max} at the 14 weather stations

future temperature and precipitation covering all 25 km grid cell over Saskatchewan will be presented.

Table 2 provides the projected T_{mean}, T_{max}, T_{min}, and total precipitation at 50th percentile for the 14 weather stations. The results of ensemble simulations indicate that there is a gradual increase in all three temperature variables from the 2030s, to the 2050s, and the 2080s for the 14 weather stations. For example, the annual average mean temperature (i.e., T_{mean}) in the City of Regina is most likely to be 8.3 °C in the 2030s, 10.5 °C in the 2050s, and 12.5 °C to the end of this century (i.e., in the 2080s). However, the projected average T_{mean} in the City of Collins Bay is most likely to be −1.6 °C (lower than 0 °C) in the 2030s, while the projected value in the 2050s is most likely to be 0.3 °C (exceed 0 °C) and the annual average mean temperature to the end of this century would be as high as 1.8 °C. Similarly, there is a gradually increasing trend in the ensemble simulations for other two temperature variables (i.e., T_{max} and T_{min}) over all 14 weather stations.

Moreover, the projected annual total precipitation at 50th percentile for all 14 weather stations is provided. Due to spatial variability of cities, the ensemble simulations suggest gradually increasing total precipitation from the 2030s–2050s for the selected stations but except for cities of Key Lake, Regina, Saskatoon, and Val-Marie. For example, the average annual total precipitation in the city of Prince Albert is most likely to be 591.8 mm in the 2030s, and it is likely increased to 603.0 mm in the 2050s; by contrast, the projected value in the city of Saskatoon decreases from 570.2 mm in the 2030s to 568.3 mm in the 2050s. In addition, there is also a consistently increasing trend in total precipitation from the 2050s to the end of this century for the selected cities but except for the weather stations of Buffalo Narrows, Estevan, Island Falls, Moosomin, Prince Albert, and Uranium City. For example, the annual total precipitation in the city of Regina is projected to be increased from 524.9 mm in the 2050s to 530.0 mm in the 2080s, while the projected value in the city of Prince Albert would be decreased from 603.0 mm in the 2050s to 596.6 mm in the 2080s.

The most likely ranges of the projected T_{mean}, T_{max}, T_{min} and total precipitation for all weather stations are provided in Figs. 3, 4, 5 and 6. It is indicated that there is a gradual increase in the spread of ranges for T_{mean}, T_{max}, T_{min} and total precipitation over most of the stations from the 2030s to the end of this century. For example, the projected range of the T_{mean} in city of Regina is most likely to be [6.2, 9.0] °C (i.e., a spread of 2.8 °C) in the 2030s, and [7.2, 11.0] °C (i.e., a spread of 3.8 °C) in the 2050s, while the projected range would expand to [8.6, 12.7] °C (i.e., a

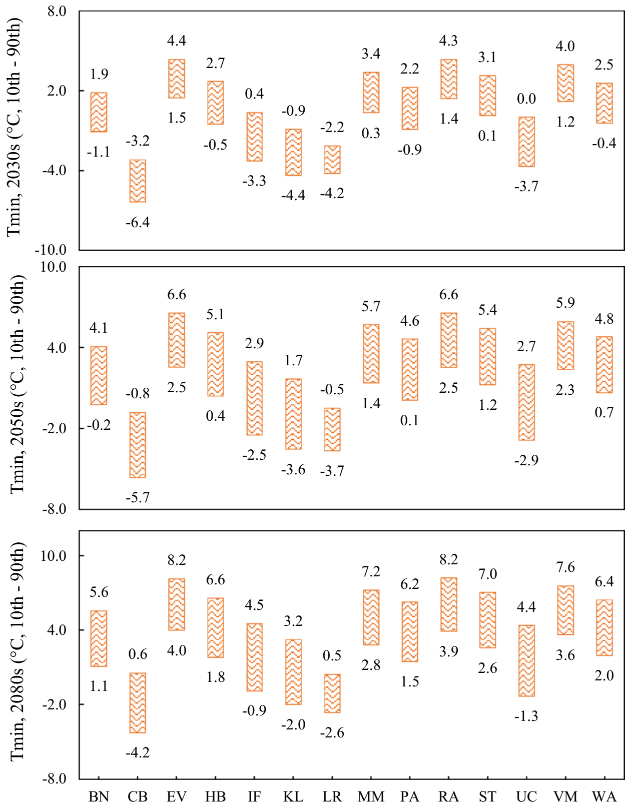


Fig. 5 Projected intervals of T_{min} at the 14 weather stations

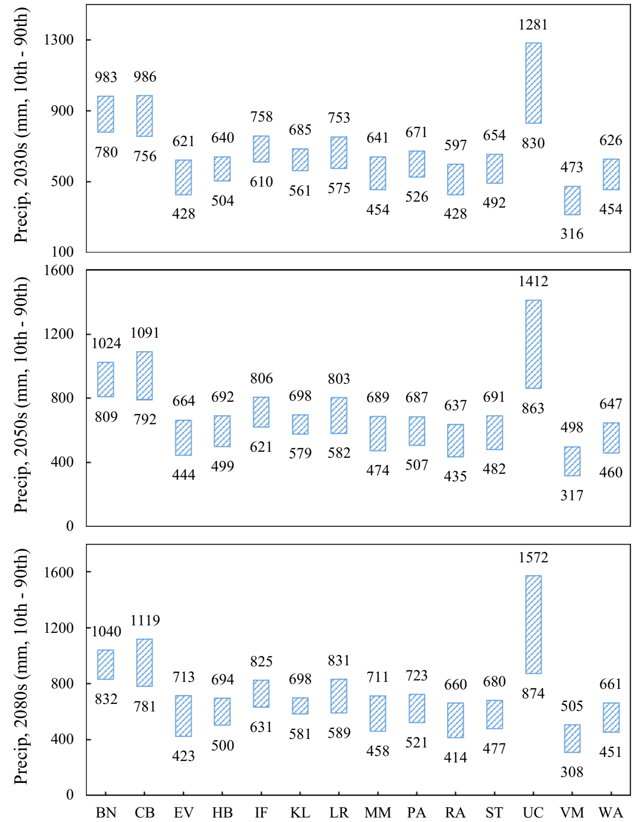


Fig. 6 Projected intervals of total precipitation at the 14 weather stations

spread of 4.1 °C) to the end of this century. However, the spread of the projected range for T_{mean} over the station of Collins Bay increases from [−3.5, −0.5] °C (i.e., a spread of 3.0 °C) in the 2030s to [−2.8, 1.7] °C (i.e., a spread of 4.5 °C) in the 2050s, and would be decreased to [−1.4, 3.0] °C (i.e., a spread of 4.4 °C) in the 2080s. Those spreads of the most likely ranges for T_{max}, T_{min}, and total precipitation can be similarly revealed over all 14 stations.

Figures 7, 8 and 9 provide the spatial distribution of the projected changes for T_{mean}, T_{max}, and T_{min} in three future periods (i.e., the 2030s, 2050s, and 2080s) at three different percentiles (10th, 50th, and 90th) for all 25 km grid cells over the whole Province of Saskatchewan. The changes of mean, minimum, and maximum temperatures show a consistent warming trend in the 2030s, 2050s, and 2080s in the PRECIS ensemble simulations throughout the whole Province of Saskatchewan. For example, the projected changes of mean temperature over the whole Saskatchewan area is [0, 2] °C in the 2030s at 10th percentile, [2, 5.5] °C in the 2050s at 50th percentile, and [3, 10] °C in the 2090s at 90th percentile. Moreover, it can be found that there is an apparently spatially increasing pattern for the projected changes of minimum temperature, which is similar to the projected changes of mean temperature. For example, the minimum change of T_{min} is projected to be above 1.0 °C in the 2030s at 10th percentile, and 2.4 °C in the 2050s at 50th percentile, while the minimum change value would be as high as 3.8 °C to the end of this century at 90th percentile. Similarly, a consistently increasing pattern in the context of Saskatchewan is also projected for maximum temperature.

Moreover, the projected spatial distribution of total precipitation changes over Saskatchewan in three future periods at three different percentiles for all 25 km grid cells is presented in Fig. 10. It is indicated that there are no significant changes in the spatial patterns of total precipitation from the 2030s to the end of this century. The minimum change of the projected total precipitation over the whole Province of Saskatchewan is most likely to be −1.3% in the 2030s, and −0.2% in the 2050s at 50th percentile, while the minimum value would be −2.1% to the end of this century. In addition, results in the projected maps reflect the spatial variability of total precipitation changes. The highest changes of precipitation are mostly distributed in the northwest regions where the change of annual total precipitation would most likely be as high as 39% in the 2080s, while the lowest changes of precipitation is projected in south and southeast area where the value would be as low as −2.1% in the 2080s at 50th percentile.

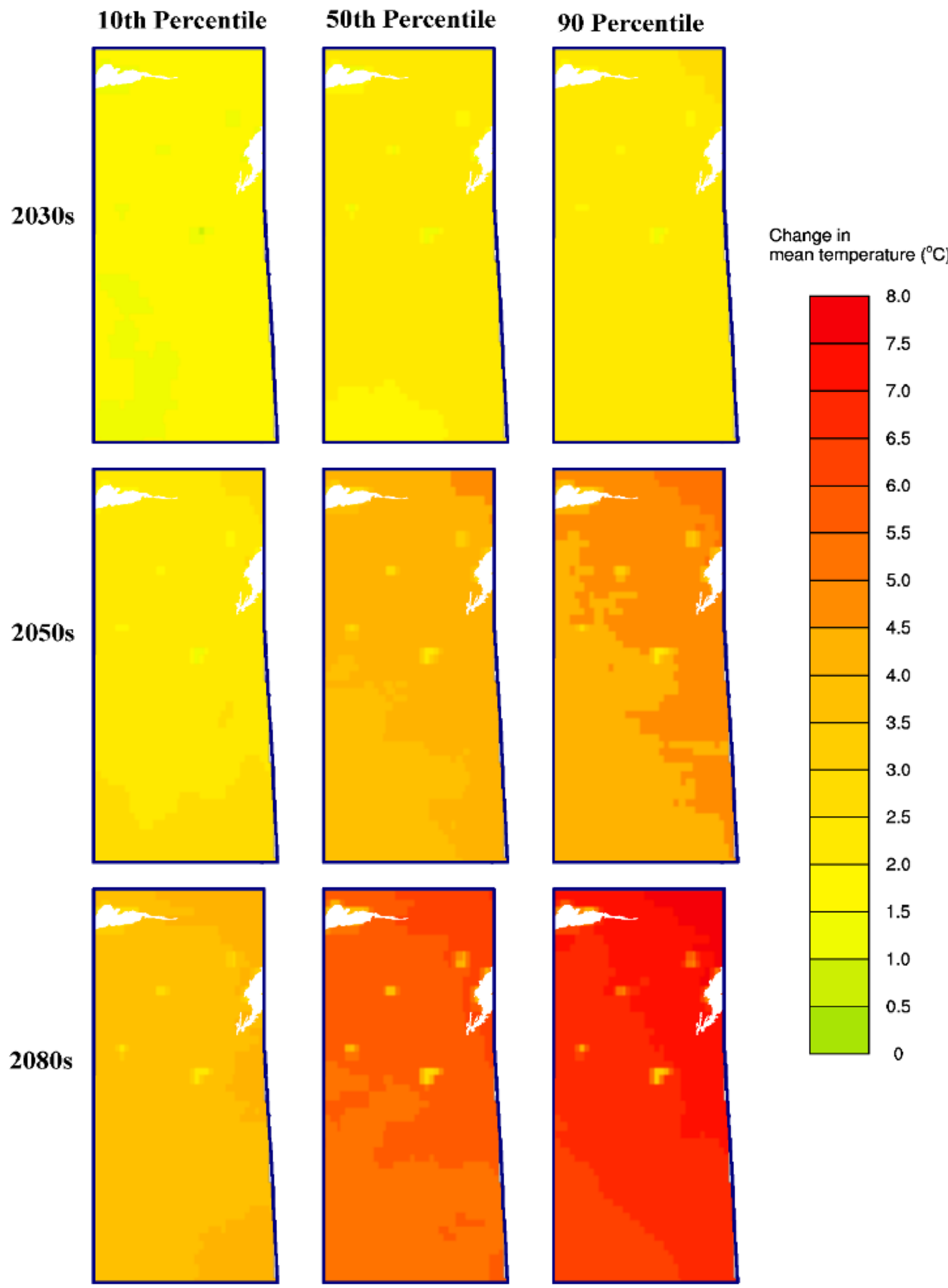


Fig. 7 Projections of T_{mean} changes at 10th, 50th, and 90th percentile for the 2030s, 2050s, and 2080s over Saskatchewan

4 Conclusions

In this study, high-resolution projections of temperatures and precipitation changes over Saskatchewan, Canada, were developed through an ensemble modeling method for supporting impact assessment of future climatic changes at local scales. The PRECIS regional climate modeling system was employed to conduct ensemble simulations over Saskatchewan from 1950 to 2099. Furthermore, the PRECIS system was driven by boundary data from a HadCM3-based perturbed physics ensemble. The performance of PRECIS ensemble simulations in capturing the current climatology over Saskatchewan was evaluated with observed data of temperature and precipitation. The future climate projections over three time slices (i.e., the 2030s, 2050s, and 2080s) were analyzed, which could help the possible effects of climate changes in the context of Saskatchewan.

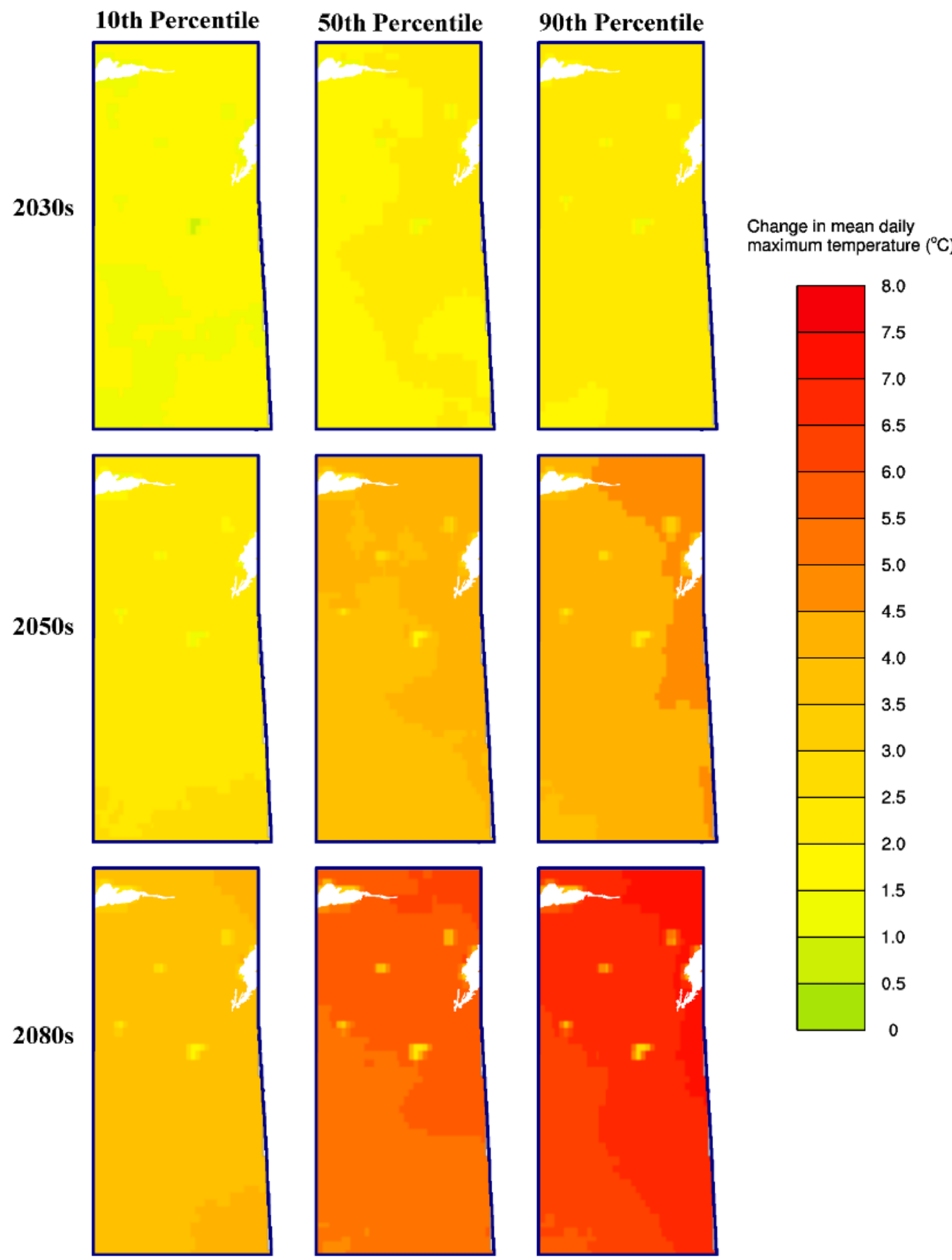


Fig. 8 Projections of T_{max} changes at 10th, 50th, and 90th percentile for the 2030s, 2050s, and 2080s over Saskatchewan

The evaluation results show that the PRECIS ensemble simulations perform very well in terms of capturing the spatial patterns of T_{mean}, T_{min}, and T_{max}, except for the substantial warm bias relative to the observations at stations. Furthermore, the ensemble simulations captured the total precipitation reasonably well. This paper presented a regional modeling approach for assessing the climate change impacts over the Province of Saskatchewan. The ensemble simulations demonstrated good performance in generating high-resolution projections of temperatures and precipitation changes through the PRECIS regional climate modeling system. The revelations and implications of the study can provide scientific information for improving adaptation strategies and supporting decision-making under climatic change.

Through this modeling study, significant changes of climatic conditions in Saskatchewan have been revealed in the upcoming decades. Firstly, the results of future climate projections over three time slices indicate that there will be an obvious warming trend from the 2030s, to

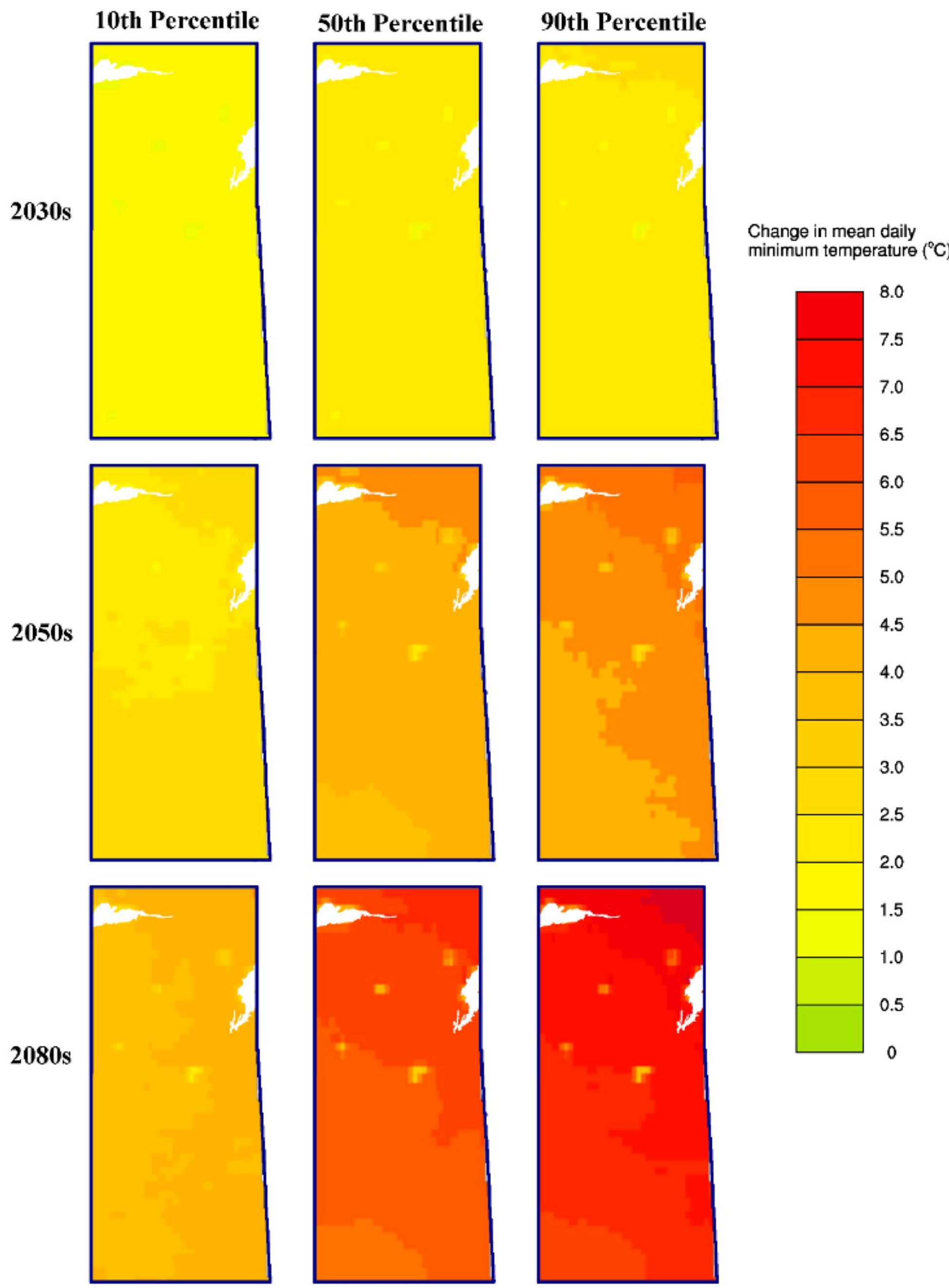


Fig. 9 Projections of T_{min} changes at 10th, 50th, and 90th percentile for the 2030s, 2050s, and 2080s over Saskatchewan

the 2050s, and the 2080s over Saskatchewan. Secondly, the results in the projected ensemble simulations also indicate that there will be no significant change in spatial patterns of total precipitation from the 2030s to the end of this century over the entire province. Thirdly, the ensemble simulations also suggest gradually increasing total precipitation from the 2030s to the 2080s in most of Saskatchewan regions. The limitation of the dynamical downscaling approach in this study is that the effects of systematic errors in the boundary data provided by GCM outputs would be transferred into the downscaled projections. Extensions of the dynamical downscaling approach in considering downscaling different GCMs would be an interesting topic that also deserves future research efforts.

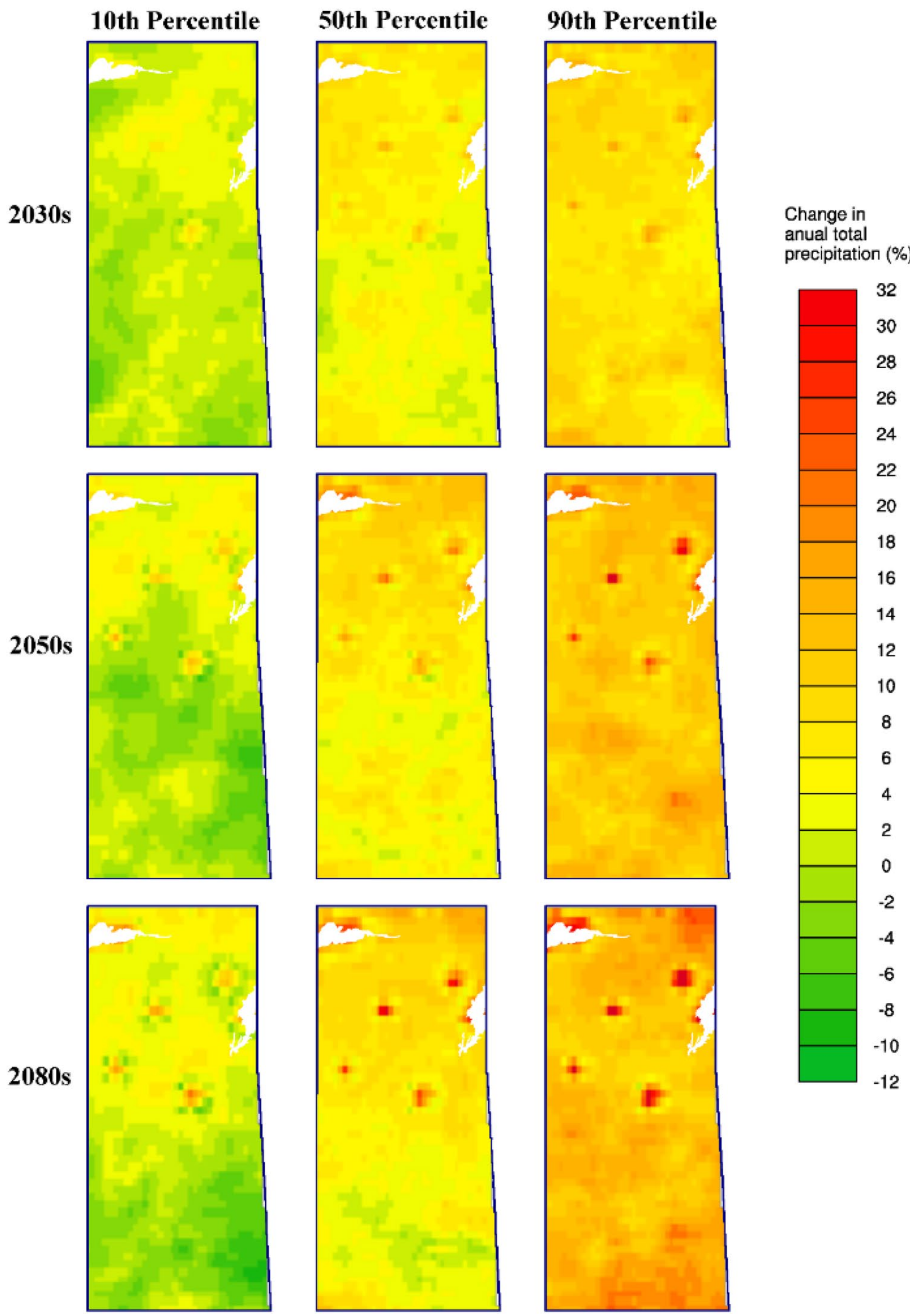


Fig. 10 Projections of Precipitation changes at 10th, 50th, and 90th percentile for the 2030s, 2050s, and 2080s over Saskatchewan

Acknowledgements This research was supported by the Natural Sciences Foundation (51190095, 51225904), the Program for Innovative Research Team in University (IRT1127), the 111 Project (B14008), and the Natural Science and Engineering Research Council of Canada.

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