PRECIS-projected increases in temperature and precipitation over Canada

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In this study, high-resolution projections of temperature and precipitation changes over Canada were developed through the Providing Regional Climates for Impact Studies (PRECIS) model under Representative Concentration Pathways (RCPs). In detail, the PRECIS model was employed to conduct simulations for the historical period over the entirety of Canada, driven by the boundary conditions from both ERA-Interim (1979–2011) and HadGEM2-ES (1959–2005). The performance of PRECIS simulations in reproducing historical climatology of Canada was then validated through comparison with observed temperature and precipitation over the baseline period (1986–2005). The boundary conditions from HadGEM2-ES under RCP4.5 and RCP8.5 was used to drive PRECIS for simulating climatic variables over Canada for the period of 2006–2099. Future climate projections of temperature and precipitation as well as their extreme indices over two time-slices (i.e. 2046–2065 and 2076–2095) were extracted and analysed. The results could help investigate how the regional climate over Canada will respond to global warming as well as the spatio-temporal characteristics of plausible climate changes in the Canadian context. The validation results demonstrate that the PRECIS model is effective in reproducing the historical climatological patterns of annual mean temperature and total precipitation across Canada. Projections of temperature and precipitation for the two future periods indicate that there will be an apparent increasing pattern over Canada. The projected changes derived in this study can provide decision-makers with valuable information to evaluate possible impacts on economic, social and environmental sectors at regional and local scales.

Key Words: climate change; dynamical downscaling; impact studies; Canada

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1. Introduction

Increasing concern has been paid to climate change in recent years due to its potential consequences. To investigate the potential impacts of climatic change, regional climate models (RCMs) have been widely employed to project future climate conditions under the Special Report on Emissions Scenarios (SRES: Nakicenovic *et al.*, 2000) or the Representative Concentration Pathways (RCPs: Van Vuuren *et al.*, 2011). RCMs have advantages in simulating regional detailed atmospheric and terrestrial processes in numerous studies (Jones *et al.*, 1995; Denis *et al.*, 2002). Moreover, as the second largest country in the world, Canada is suffering a higher warming rate than the global rate (Environment and Climate Change Canada, 2016). This will have significant impacts on Canada's economic activity sectors such as agriculture and forestry, and it necessitates a better understanding of how climate will change in a Canadian context to support proper mitigation and adaptation strategies (Maurer *et al.*, 2007; IPCC, 2013).

Previous studies have attempted to obtain high-resolution regional climate simulations and future projections over Canada through RCMs (Plummer *et al.*, 2006; Sushama *et al.*, 2010; Mladjic *et al.*, 2011; Jeong *et al.*, 2016a, 2016b). Through nesting RCMs into General Circulation Models (GCMs), improved simulation of GCMs can be achieved and projections for temperature and precipitation variables can be generated at finer spatial scales (Lavender and Walsh, 2011; White *et al.*, 2013; Wang *et al.*, 2015a). For instance, Jeong *et al.* (2016a) investigated projected changes in winter period cold extreme days (i.e. cold nights, cold days, frost days and ice days) and cold spells over Canada based on 11 RCMs. Mladjic *et al.* (2011) projected changes in extreme precipitation characteristics over Canada by using the Canadian Regional Climate Model (CRCM), which mainly focused on an assessment corresponding to the SRES A2 emissions scenario (Sushama *et al.*, 2010). Sushama *et al.* (2010) presented the CRCM projected changes in dry spell characteristics (i.e. extended periods of dry days) over Canada, for the April–September period, and their validation in current climate conditions. Plummer *et al.* (2006) provided an analysis of several multi-decadal simulations of the present (1971–1990) and future (2041–2060) climate from CRCM with radiative forcing specified by the SRES A2 scenario.

For Canada, in general, although several RCMs have been implemented, they have been based on the SRES; there have been few modelling efforts (Šeparović *et al.*, 2013; Wang and Kotamarthi, 2015) to dynamically downscale climatic changes under the RCPs as recommended by the Intergovernmental Panel on Climate Change (IPCC) in 2013 (Van Vuuren *et al.*, 2011; IPCC, 2013). The RCPs have advantages in (i) providing more detailed information for running the current generation of climate models, (ii) exploring impacts of different climate policies compared to the no-climate-policy scenarios explored so far (e.g. SRES), and (iii) investigating the role of adaptation in more detail (Van Vuuren *et al.*, 2011). Recently, the PRECIS model has been employed to dynamically downscale temperature and precipitation changes under SRES in the Provinces of Saskatchewan and Ontario, Canada (Wang *et al.*, 2014, 2015c; Zhou *et al.*, 2017). They found that the PRECIS model can be an effective tool in reproducing the historical climate.

Therefore, the objective of this study is to develop high-resolution regional climate projections of temperature and precipitation over Canada using the PRECIS model under two RCPs. Specifically, the PRECIS model will be employed to conduct simulations for the historical period over the entirety of Canada, driven by the boundary conditions from both ECMWF reanalysis ERA-Interim (1979–2011) and Hadley Centre HadGEM2-ES (1959–2005). Based on the comparison with observed temperature and precipitation, the performance of PRECIS simulations in reproducing the historical climatology of Canada will then be validated. The boundary conditions from HadGEM2-ES under RCP4.5 and RCP8.5 will be used to drive PRECIS for simulating climatic variables over Canada for the period of 2006–2099. Future climate projections of temperature and precipitation as well as their extreme indices over two time-slices (i.e. 2046–2065 and 2076–2095) will then be extracted and analysed. The results could help investigate how the regional climate over Canada would respond to global warming as well as the spatio-temporal characteristics of plausible climate changes in the Canadian context. It is expected that changes in climatic conditions will be explored more fully in the upcoming decades. The projected changes derived in this study can provide decision makers with valuable information to avoid severe impacts of climatic changes on economic, social and environmental sectors at regional and local scales.

2. Model, data, and study area

2.1. *Regional climate modelling*

In this study, the updated version of the Providing Regional Climates for Impact Studies (PRECIS) regional climate modelling system (PRECIS2.0) developed by the UK Hadley Centre is employed to develop high-resolution physically based climate projections over Canada. The framework is built upon a hydrostatic, primitive equation grid-point model, which comprises 19 levels described by a combination of σ-coordinate and pressure coordinate (Wilson *et al.*, 2005). The PRECIS model can provide a minimum resolution of 50 km × 50 km and 25 km × 25 km at the Equator of the rotated grid with two different horizontal resolutions: $0.44^\circ \times 0.44^\circ$ and $0.22^\circ \times 0.22^\circ$, respectively (Wang *et al.*, 2014; Centella-Artola *et al.*, 2015). The radiation scheme includes the seasonal and diurnal cycles of insolation, computing short-wave and long-wave fluxes (Jones *et al.*, 2004). The Met Office Surface Exchange Scheme is employed as the land-surface model component (Cox *et al.*, 1999). The convective scheme is the mass flux penetrative scheme with an explicit downdraught (Jones *et al.*, 1995). The detailed model parametrization is described by Jones *et al.* (2004). The model can be easily employed to provide detailed regional climate change projections for impact studies (Jones and Hassell, 2004; Wang *et al.*, 2015c).

The initial and lateral boundary conditions of PRECIS are derived from the ERA-Interim (1979–present) as well as the HadGEM2-ES historical experiment (1959–2005) and future experiments under RCPs (2006–2099). The ERA-Interim covering the period from 1979 to present is the latest reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee *et al.*, 2011). RCPs including RCP2.6, RCP4.5, RCP6, and RCP8.5 are generally different from each other after 2050. More details are described in Moss *et al.* (2010).

In this study, the PRECIS simulations are performed at a horizontal resolution of $0.44^\circ \times 0.44^\circ$ (i.e. 50 km), driven by boundary data from both ERA-Interim reanalysis (1979–2011) and the HadGEM2-ES historical experiment (1959–2005) with the purpose of providing full simulations for present-day climate conditions. The experimental domain over North America consists of 131 (longitude) × 113 (latitude) grid points covering all of Canada. Figure 1 shows the domain and the topography as resolved through PRECIS. Outputs from the PRECIS simulations are then extracted and split into three 20-year periods, including 1986–2005 (the baseline period), 2046–2065 (or 2050s), and 2076–2095 (or 2080s). Based on IPCC (2013), the data for the period of 1986–2005 is extracted to represent the baseline period, while the extracted simulations in the 2050s and 2080s are employed to represent the medium-term and long-term future, respectively.

2.2. *Observations of current climate*

To validate the performance of PRECIS in capturing the historical Canadian climatology, the gridded observation datasets of monthly precipitation and daily temperature variables (T_{mean}, T_{min} and T_{max} hereafter) were obtained from the Climate Research Unit's Time-Series (CRU TS 3.21: Jones and Harris, 2013). Based on an analysis of over 4000 individual weather station records, the CRU TS 3.21 dataset was gridded to a spatial resolution of $0.5^\circ \times 0.5^\circ$ for the period of 1901–2012 (Jones and Harris, 2013). The data for the period of 1986–2005 were extracted to represent the historical climate observations in the Canadian context.

2.3. *Study area*

Canada is the second largest country in the world, and is bordered by the Atlantic Ocean to the east, the Pacific Ocean in the west and the Arctic Ocean to the north (Figure 1). The geography of Canada varies from the Rocky Mountains to boreal forests, prairies, desert and rainforest regions. With a current population of more than 36.2 million, Canada has a total surface area of 10 million km^2 (Statistics Canada, 2005). Central Canada and northern Canada have subarctic and arctic climates, while the Canadian cities located offshore on the west and east coasts have an oceanic climate.

Warming rates in Canada are about twice of the global rate (Environment and Climate Change Canada, 2016). Effects will persist for centuries due to the long-lived greenhouse gases (GHGs) and warming oceans (Environment and Climate Change Canada, 2016). Moreover, changes in cold temperature levels and associated extremes such as cold spells in winter will have significant impacts on human health, leading to environmental hazards and severe disruptions in economic activities (Shabbar and Bonsal, 2003). Such changes in cold temperature extremes are already being experienced in Canada. For example, Shabbar and Bonsal (2003) described that there were decreases (increases) in the observed frequency and duration of cold spells in the west (east) of Canada during the period 1950–1998. Vincent and Mekis (2006) reported that there are decreasing trends in

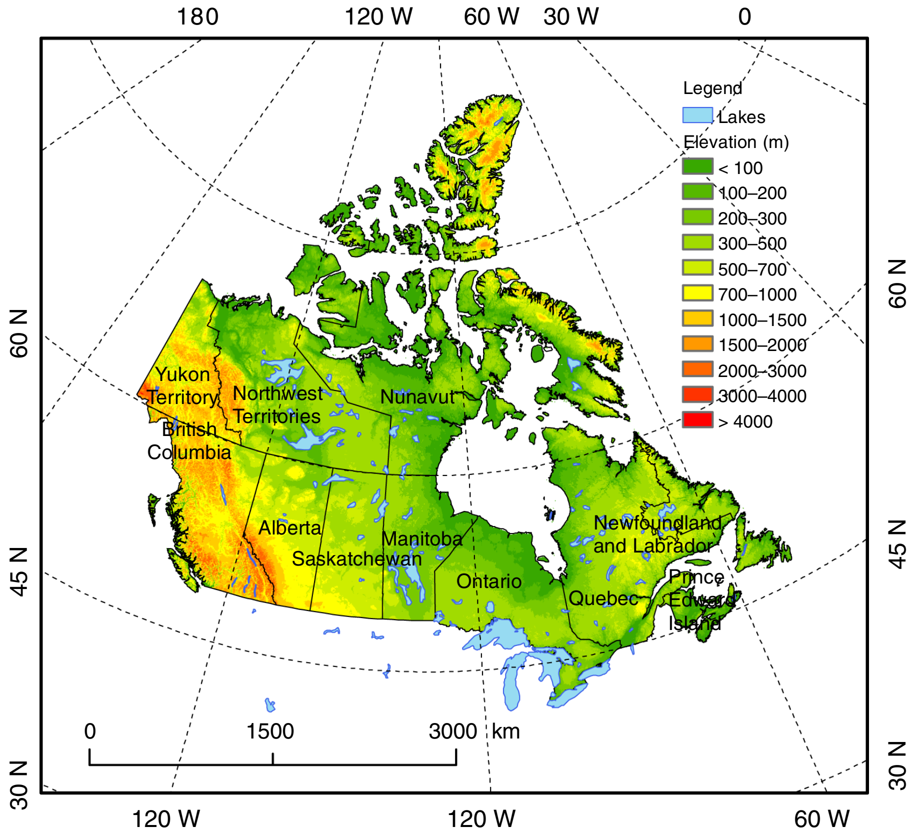

Figure 1. Topography of the study region. [Colour figure can be viewed at wileyonlinelibrary.com].

observed cold days, cold nights, and frost days for the 1950–2003 period. Therefore, a regional climate modelling approach under RCPs is desired for exploring the implications of temperature and precipitation changes over Canada in both the short and long term.

3. Results

3.1. Evaluation of the PRECIS simulations

In order to evaluate the performance of the PRECIS model in capturing the historical climate, the precipitation and temperature variables for the period of 1986–2005 are first extracted from ERA-Interim, ERA-PRECIS (i.e. PRECIS driven by ERA-Interim reanalysis), HadGEM2-ES, and Had-PRECIS (i.e. PRECIS driven by HadGEM2-ES). Through comparison with the CRU observations (i.e. T_{max}, T_{min}, T_{mean} and precipitation) over the country of Canada directly, the capability of the PRECIS model can be evaluated. Figure 2 presents the spatial distribution of annual temperature and precipitation variables from the CRU observations and simulations of ERA-Interim, ERA-PRECIS, HadGEM2-ES and Had-PRECIS for the historical period from 1986 to 2005.

Compared with observations (Figure 2(d)) in the historical period, ERA-Interim (Figure 2(a)) slightly overestimates annual mean temperature in the southwestern region, while T_{mean} in the northeastern region is underestimated. For example, the annual mean temperature from ERA-Interim (Figure 2(a)) would be approximately 3 °C higher than that from CRU (Figure 2(e)) in a small area of the southwestern region, leading to warm biases in the simulation. In contrast, we found that the ERA-PRECIS (Figure 2(c)) performs better in simulating annual mean temperature in the northeastern region in spite of warm biases in the southwestern region. As shown in Figures 2(c) and (d), HadGEM2-ES and Had-PRECIS could capture the general pattern of annual mean temperature with a transition from high temperature in southwestern Canada to low temperature in northeastern Canada. Although there are warm biases in the southwestern region, the results (Figure 2(A)) indicate that better performance is found from Had-PRECIS in reproducing T_{mean} over the majority of Canada in the historical period of 1986–2005.

Similar implications could be drawn from the comparison results for two other temperature variables (i.e. minimum and maximum temperature) reproduced from ERA-Interim, ERA-PRECIS, HadGEM2-ES and Had-PRECIS (Figures 2(B) and (C)). It is indicated that the performance of both ERA-PRECIS and Had-PRECIS in reproducing T_{min} are better than their driving GCMs (i.e. ERA-Interim and HadGEM2-ES) over the northeastern region. However, as for annual maximum temperature (Figure 2(C)), ERA-Interim and HadGEM2-ES tend to underestimate it over the majority of Canada. This is especially true in northeastern Canada, which could be as much as 9 °C lower than the observations (Figure 2(j)). The results indicate that both ERA-PRECIS and Had-PRECIS perform well in simulating T_{max} in Canada for the historical period.

In general, the comparison results of annual total precipitation (Figure 2(D)) indicate that ERA-Interim, ERA-PRECIS, HadGEM2-ES and Had-PRECIS could capture spatial patterns in the historical period. However, the wet biases reproduced from ERA-Interim and HadGEM2-ES are larger than from ERA-PRECIS and Had-PRECIS. Moreover, ERA-PRECIS and Had-PRECIS have captured the total precipitation much better than their driving GCMs. This also implies that Had-PRECIS simulates more reliable spatial distribution of annual total precipitation over Canada in the historical period. Figure 3 further presents the differences between Had-PRECIS and CRU for temperature and precipitation variables during 1986–2005 over Canada. The results (Figures 3(a)–(c)) indicate that there are larger warm biases in temperature variables over the southwestern region than over the northeastern region, while the precipitation is overestimated over the northwestern region and underestimated over the southeastern region.

Taylor diagrams (Taylor, 2001) are employed to evaluate spatial variability and the correlation of both annual and seasonal simulation (T_{mean}, T_{min}, T_{max} and precipitation) over the entire Canadian domain relative to the CRU observations.

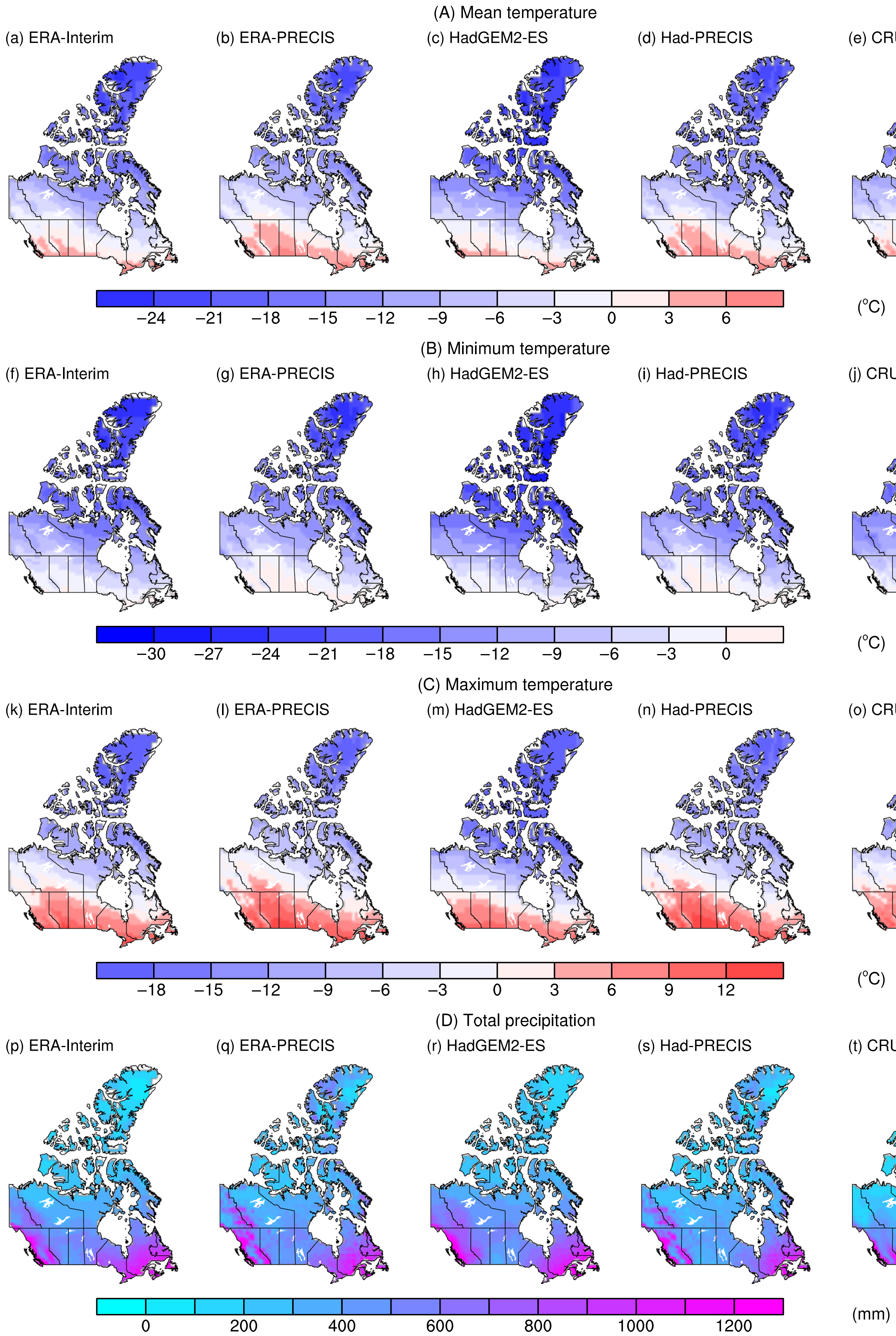

Figure 2. Spatial distributions of (A)–(C) temperature and (D) precipitation for 1986–2005 over Canada from (a,f,k,p) ERA-Interim, (b,g,l,q) ERA-PRECIS, (c,h,m,r) HadGEM2-ES, (d,i,n,s) Had-PRECIS, and (e,j,o,t) observations. [Colour figure can be viewed at wileyonlinelibrary.com].

The method is able to compare correlation coefficient (COR), standard deviation, and root-mean-square error (RMSE) within a two-dimensional (2-D) graph (Taylor, 2001). In a Taylor diagram, it is considered to be a better agreement if there is a smaller gap between the compared object and the reference object (Bao *et al.*, 2015). Figure 4 presents the comparison of ERA-Interim, ERA-PRECIS, HadGEM2-ES and Had-PRECIS with respect to observations. Generally, the results further demonstrate that Had-PRECIS performs better than its driving HadGEM2-ES in simulating spatial distributions of temperature and precipitation variables. Moreover, the performance of Had-PRECIS in simulating total precipitation is not as good as that in simulating temperature. The highest correlation is achieved in winter (0.83), while the lowest one is obtained in summer (0.58).

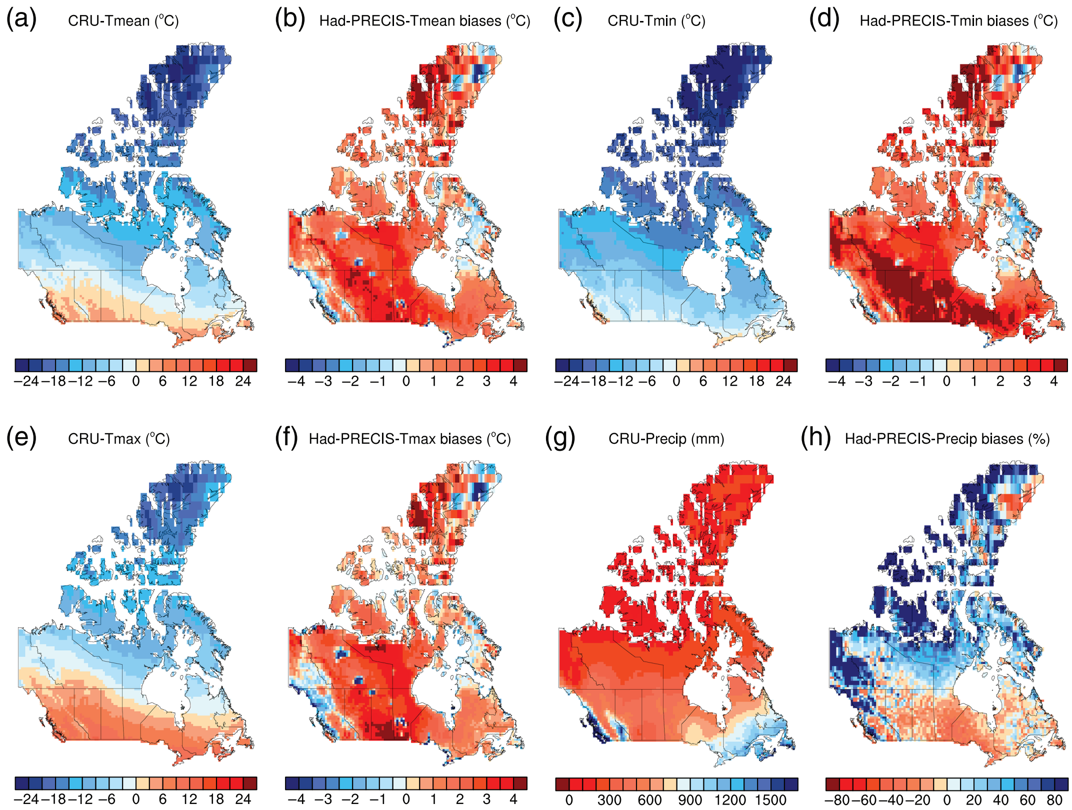

Figure 3. (a,c,e,g) Observations and (b,d,f,h) differences between Had-PRECIS and observations for (a–f) temperature and (g,h) precipitation during 1986–2005 over Canada. [Colour figure can be viewed at wileyonlinelibrary.com].

In addition, the correlations in spring and autumn are 0.80 and 0.79, respectively. This is mainly because precipitation is more difficult to simulate than temperature due to its spatial variability and nonlinear nature (Maraun *et al.*, 2010).

The frequencies of occurrence are defined as the rate at which temperature or precipitation occurs over a particular range in all grid cells over the entirety of Canada. Data sample from all grid cells are taken into account for this validation. Figure 5 presents frequencies of occurrence of annual temperature and precipitation from CRU observations and different model simulations over the Canadian domain. It is evident that the Had-PRECIS simulation is able to capture the general frequency distributions of temperature and precipitation variables over the entirety of Canada. For example, the results for mean temperature indicate that Had-PRECIS overestimates the frequencies of mean temperature between 4 and 8 °C. Nevertheless, the frequencies of mean temperature between −20 and −16 °C are underestimated by the Had-PRECIS simulations. In contrast, HadGEM2-ES tends to overestimate the frequencies of temperature variables below −20 °C. Moreover, Had-PRECIS simulates lower frequencies of precipitation below 200 mm, and predicts relative higher frequencies of precipitation between 200 and 400 mm.

In addition, Figure 6 presents spatial distributions of standard deviations of annually averaged temperature and precipitation variables for the historical period of 1986–2005. It is indicated that Had-PRECIS could generally capture the magnitude and patterns of temporal variability of annually averaged temperature variables. For example, the temporal variability of annually averaged T_{mean} over the majority of Canada is well reproduced by Had-PRECIS in spite of slightly large biases in central Canada. Moreover, the magnitudes of standard deviation are underestimated by the Had-PRECIS simulation. However, the Had-PRECIS simulation performs very well in simulating the spatial pattern of temporal variability of annually averaged precipitation.

Overall, the validation results indicate the PRECIS model can be an effective tool in reproducing the historical climatological patterns of annual temperature (mean, maximum and minimum temperature) and total precipitation across Canada. It is also demonstrated that the PRECIS model can add some value to the HadGEM2-ES simulations, especially in capturing the spatial variability and the pattern correlation over Canada. This can be attributed to the more detailed description of atmospheric and terrestrial processes in the PRECIS model (Qin and Xie, 2016). Moreover, we found that the PRECIS model showed a slightly poor performance in simulating T_{min} over the southwestern region, further leading to warm biases in annual mean temperature. It is also indicated that the PRECIS model was not fully capable of capturing the biogeophysical processes dominated by T_{min} over the Rocky Mountains.

3.2. *Projected increases in temperature and precipitation*

The projected temperature and precipitation over Canada under RCP4.5 and RCP8.5 for the period 2006–2099 are developed through the PRECIS model. In order to further analyse future spatial patterns of temperature and precipitation over Canada, the projections for this century are thus divided into two 20-year periods: 2050s (2046–2065) and 2080s (2076–2095). The changes in one precipitation variable (i.e. total precipitation) and three temperature variables (i.e. T_{max}, T_{mean} and T_{min}) are calculated for each 20-year period to provide a better understanding of possible climatological features. The maps of projected annual and seasonal changes for temperature and precipitation covering all 50 km grid cells over Canada under RCP4.5 and RCP8.5 are presented. Moreover, the projected changes in frequency distribution in the context of Canada are analysed under two RCPs.

The projected changes in T_{mean}, T_{min} and T_{max} for all 50 km grid cells over the entire Canadian region in two future periods (i.e. the 2050s and 2080s) under RCP4.5 are presented in Figure 7. The changes in mean, minimum and maximum temperatures suggest a consistent increasing trend under RCP4.5 for the 2050s and 2080s in the PRECIS simulation throughout the Canadian region. For example, the results suggest that the projected changes in mean temperature for the 2050s under RCP4.5 will be [−1,

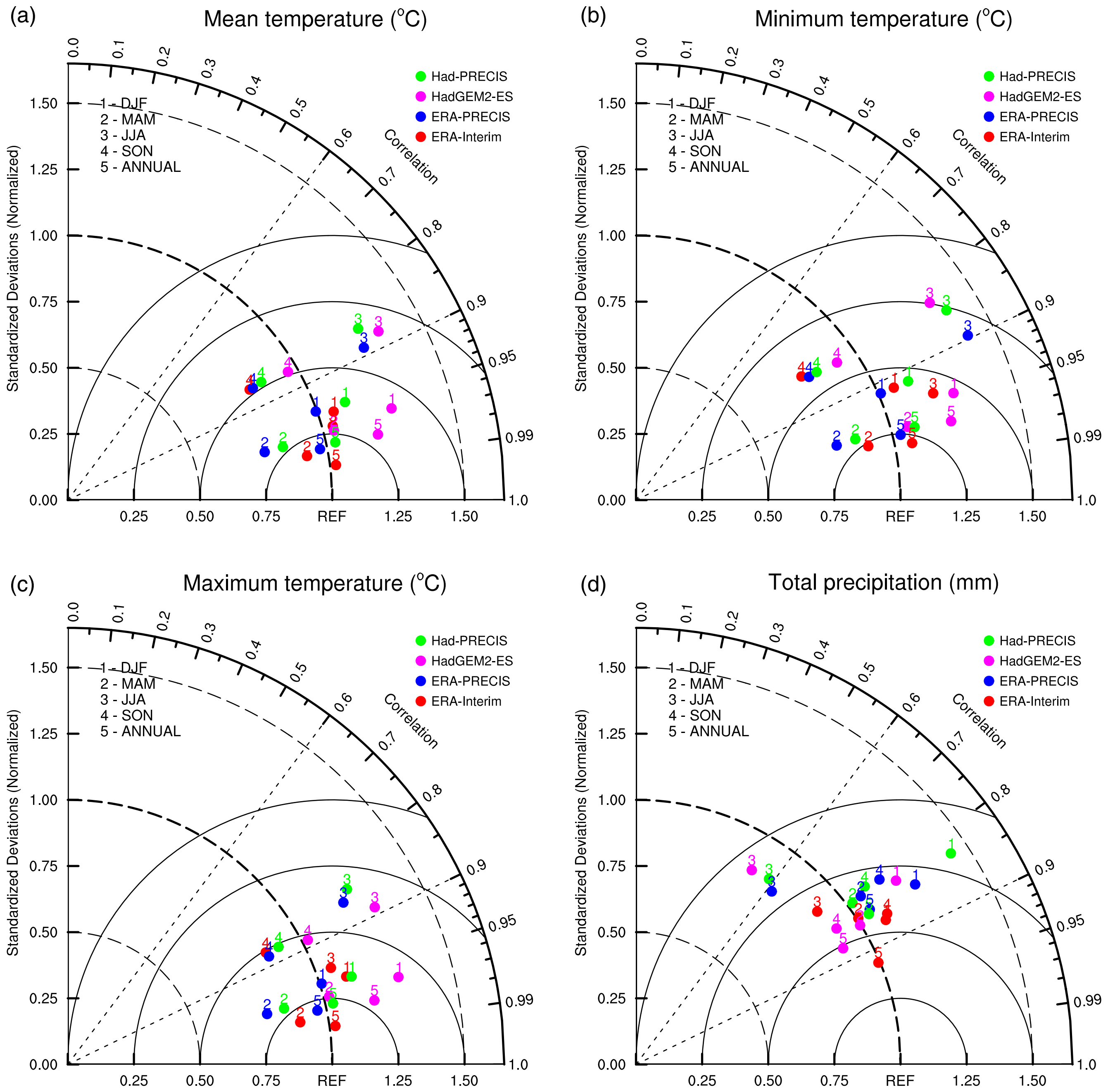

Figure 4. Taylor diagrams for annual/seasonal (a–c) temperature and (d) precipitation from ERA-Interim, ERA-PRECIS, HadGEM2-ES, Had-PRECIS for the historical period. [Colour figure can be viewed at wileyonlinelibrary.com].

3] °C in southwestern Canada and [2, 4] °C in the northeast (here, the notation [a, b] is defined as a range from the lower bound a to upper bound b). However, the projected values for the 2080s are increased by [0, 4] °C in the southwest area and [3, 8] °C in northeastern Canada. Moreover, it was found that the PRECIS simulation tends to project smaller increases in T_{mean} over the southwestern region compared to the northern area. Likewise, there is an apparent spatially increasing pattern for the projected changes in T_{min} from the PRECIS simulation under RCP4.5, which is similar to the projected changes in mean temperature. Such a consistent warming trend will drive the minimum temperature increase in the southwestern area up to as high as 3 °C for the 2050s and as high as 4 °C for the 2080s. In the northeast, the minimum temperature will be driven up to as high as 4 °C for the 2050s and as high as 8 °C for the 2080s. A similarly increasing pattern for T_{max} in the Canadian context is also projected. The projected highest increase in the southwest is 3 °C for the 2050s and 4 °C for the 2080s, while the smallest increase in the northeast is projected to be 3 °C. The greater warming at higher northern latitudes is expected because of the loss of the snow cover and therefore changes in snow albedo feedback, which would reduce the reflection of sunlight to the north (Gregory *et al.*, 2004).

To understand the projected dynamics of precipitation changes across the Canadian domain spatially, percentage changes for the two future periods under RCP4.5 are also presented in Figure 7. Total precipitation is projected to increase over the majority of the country in the 2050s and 2080s. The results also indicate that the precipitation projection for the 2080s will probably be wetter than the 2050s over the majority of Canada under RCP4.5. However, the projections show a significant decrease over southwestern and southeastern Canada for the 2050s and 2080s under RCP4.5. For instance, the PRECIS projected increase in total precipitation over the majority of Canada in the 2050s will be as much as 31%, while the decrease in total precipitation will be as low as 35%. The highest increases are expected to occur over the northern regions, while the largest decreases are expected to occur in the southeast. The projected changes in total precipitation exhibit higher spatial variability over the entire region in the 2080s. For example, total precipitation in the 2080s under RCP4.5 is projected to increase by as much as 38%, which is expected to occur in northern Canada. In contrast, the decreases in total precipitation in the

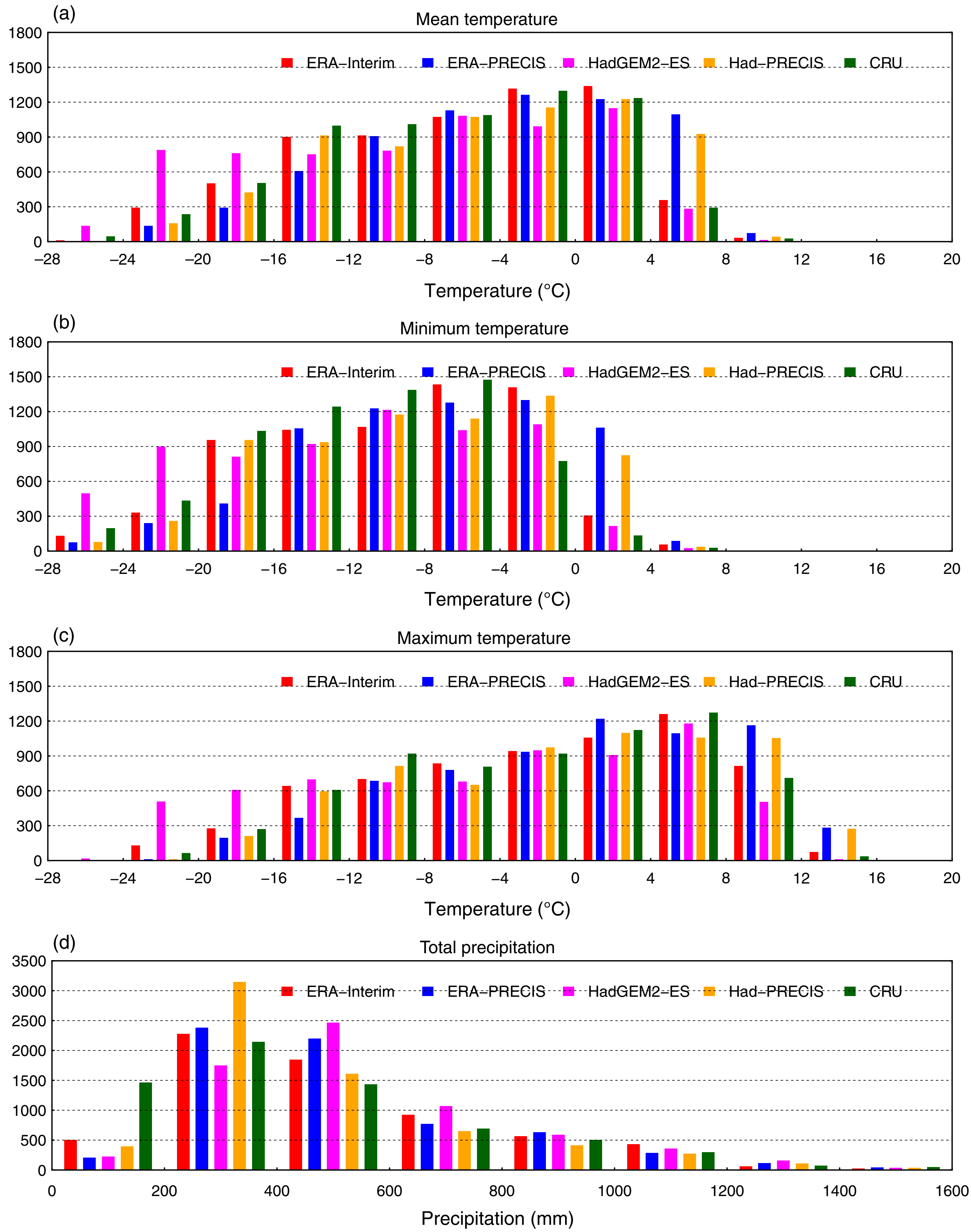

Figure 5. Frequencies of occurrence of annual (a–c) temperature and (d) precipitation from different simulations and observations over the Canadian domain in the period 1986–2005. [Colour figure can be viewed at wileyonlinelibrary.com].

2080s under RCP4.5 will be projected as low as 32%, which is projected for the southeast.

Based on the IPCC's RCP8.5 scenario, the projected changes in T_{mean}, T_{min}, T_{max} and total precipitation are analysed for the future periods (i.e. 2050s and 2080s) with respect to the present period. Figure 8 shows the results of the PRECIS simulations driven by the HadGEM2-ES global model dataset under RCP8.5. In general, the spatial patterns of changes to the temperature and precipitation variables under RCP8.5 in most cases are basically similar to those under RCP4.5, but the magnitudes of changes are different. The results from the PRECIS simulations under RCP8.5 also tend to have a larger associated variability. This is mainly because the sensitivity of future projections increases with GHG concentrations (Asong *et al.*, 2016). For example, the

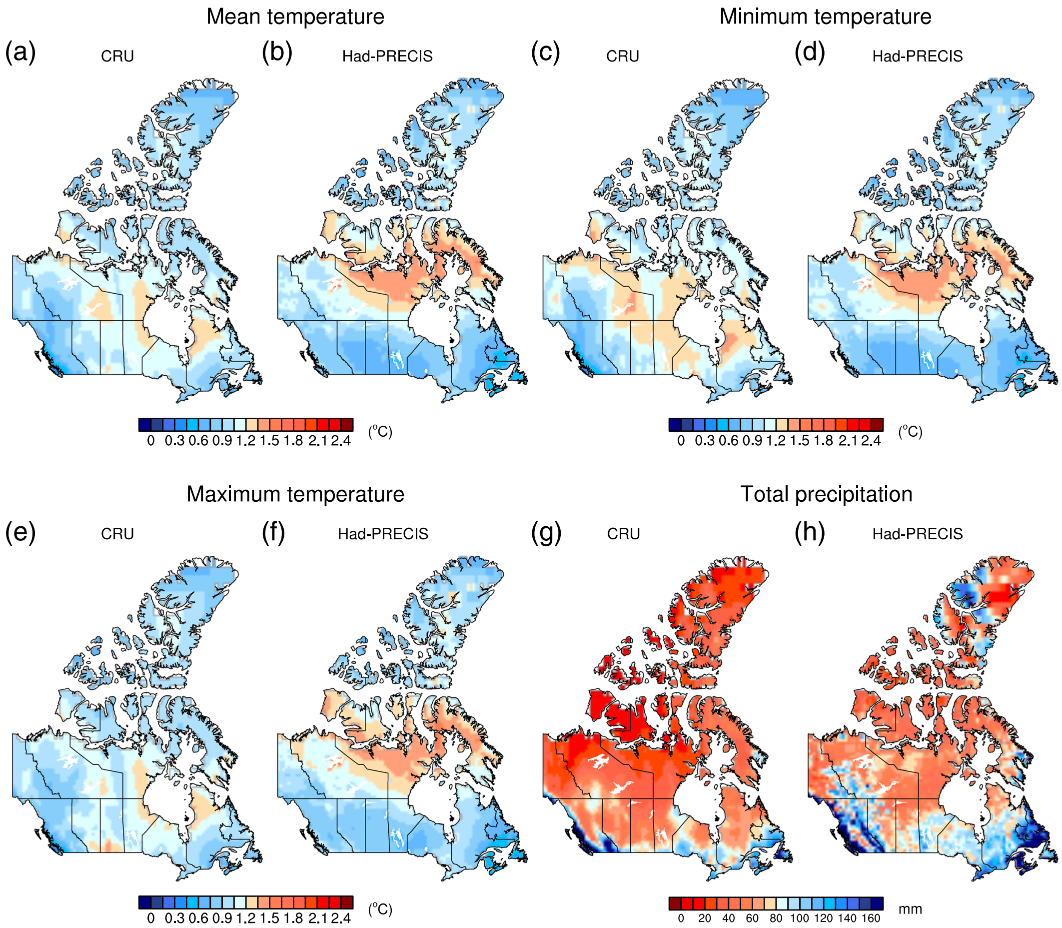

Figure 6. Spatial distributions of standard deviations of annually averaged (a–f) temperature and (g,h) precipitation for 1986–2005 over Canada from (a,c,e,g) observations and (b,d,f,h) Had-PRECIS. [Colour figure can be viewed at wileyonlinelibrary.com].

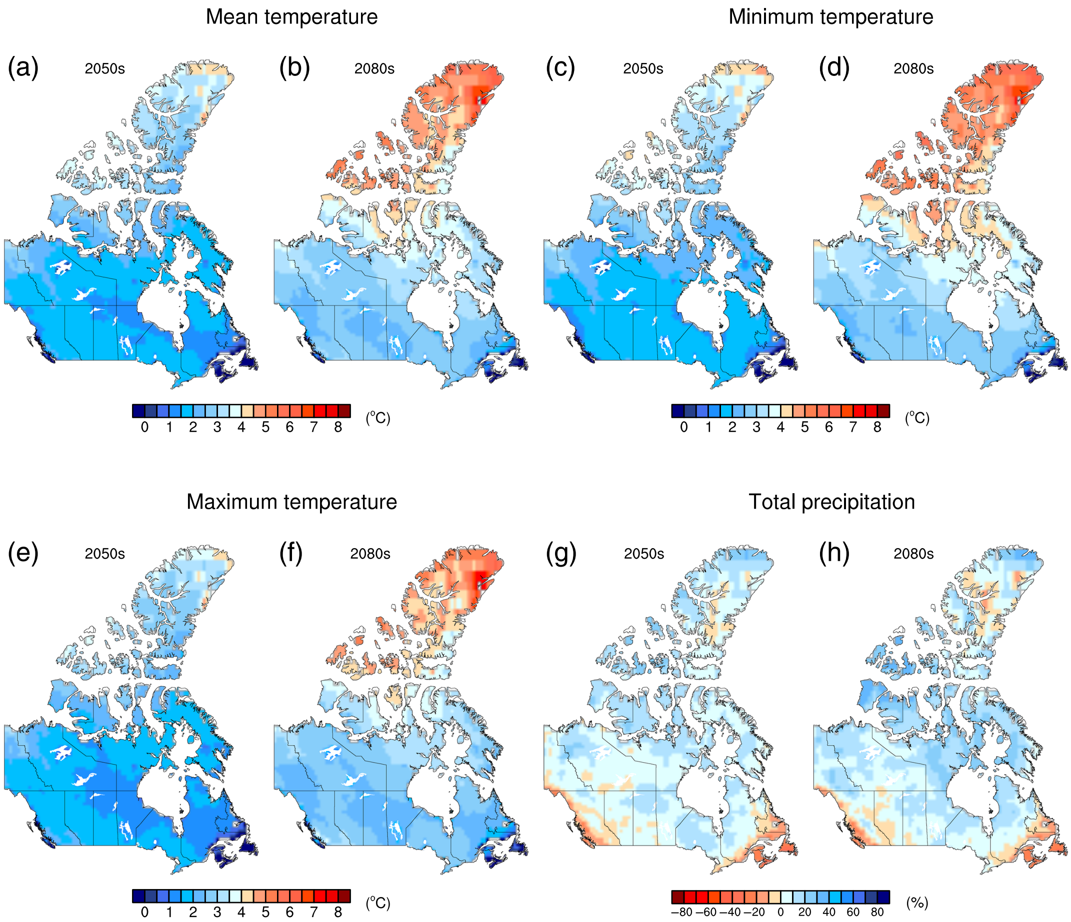

Figure 7. Spatial distributions of projected changes in annual (a–f) temperature and (g,h) precipitation for the (a,c,e,g) 2050s and (b,d,f,h) 2080s under RCP4.5. [Colour figure can be viewed at wileyonlinelibrary.com].

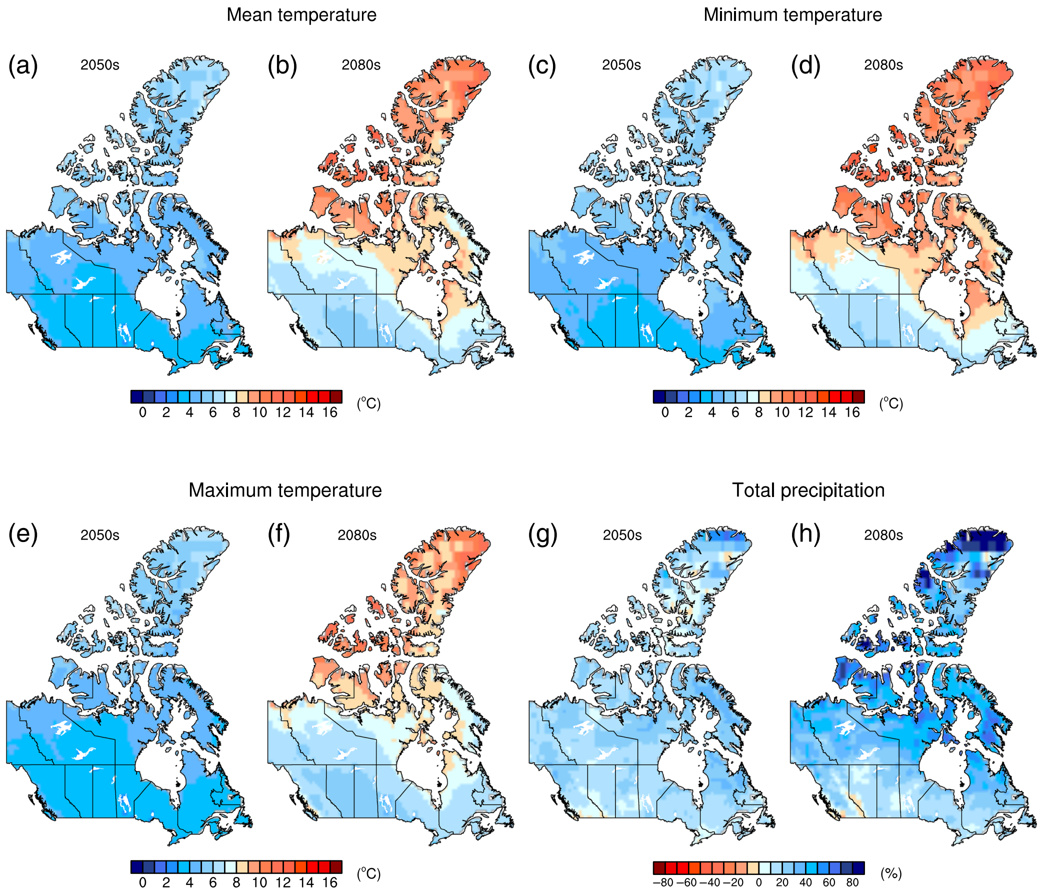

Figure 8. Spatial distributions of projected changes in annual (a–f) temperature and (g,h) precipitation for the (a,c,e,g) 2050s and (b,d,f,h) 2080s under RCP8.5. [Colour figure can be viewed at wileyonlinelibrary.com].

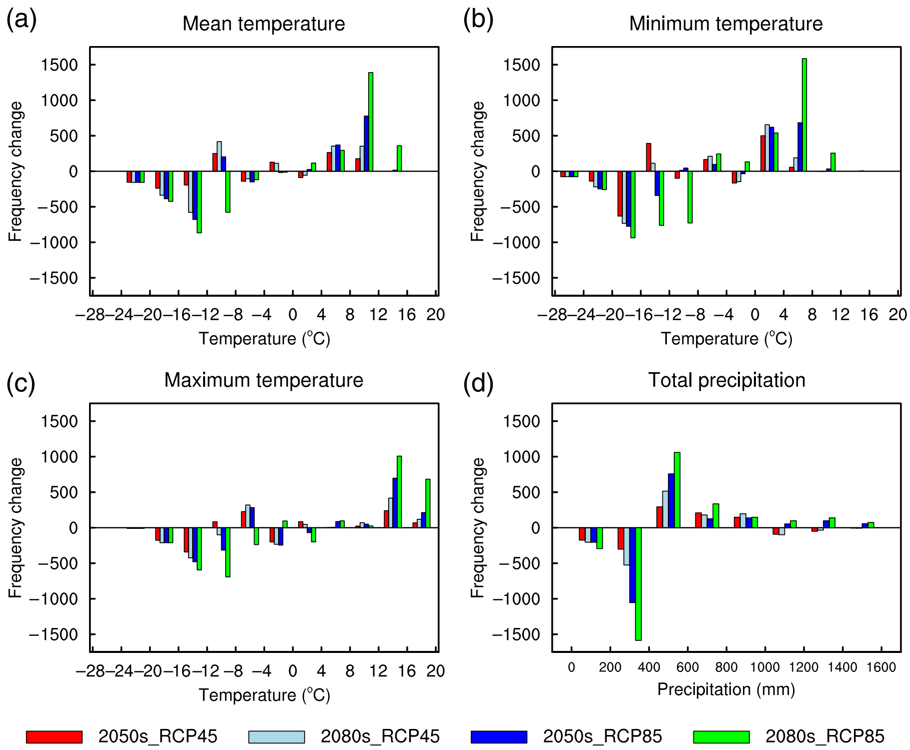

Figure 9. Spatial changes in the (a–c) temperature and (d) precipitation frequency between the future periods (i.e. the 2050s and 2080s) and the baseline period (1986–2005). [Colour figure can be viewed at wileyonlinelibrary.com].

projected changes in the three temperature variables (i.e. T_{mean}, T_{min} and T_{max}) increase by as much as 4.5 °C in southern Canada for the 2050s, while the changes to those variables are projected to increase by as much as 7.8 °C in the north. The changes are projected to be intensified in the 2080s relative to the 2050s due to the increased GHG concentrations. For instance, the highest change to the mean temperature in the 2080s is simulated in the northern region (12 °C), while the lowest changes are projected in the southwest (4 °C). However, unlike projections under RCP4.5, the total precipitation under RCP8.5 is projected to significantly increase over the entire region from the 2050s to 2080s, except in small areas in the southwest where decreases are projected.

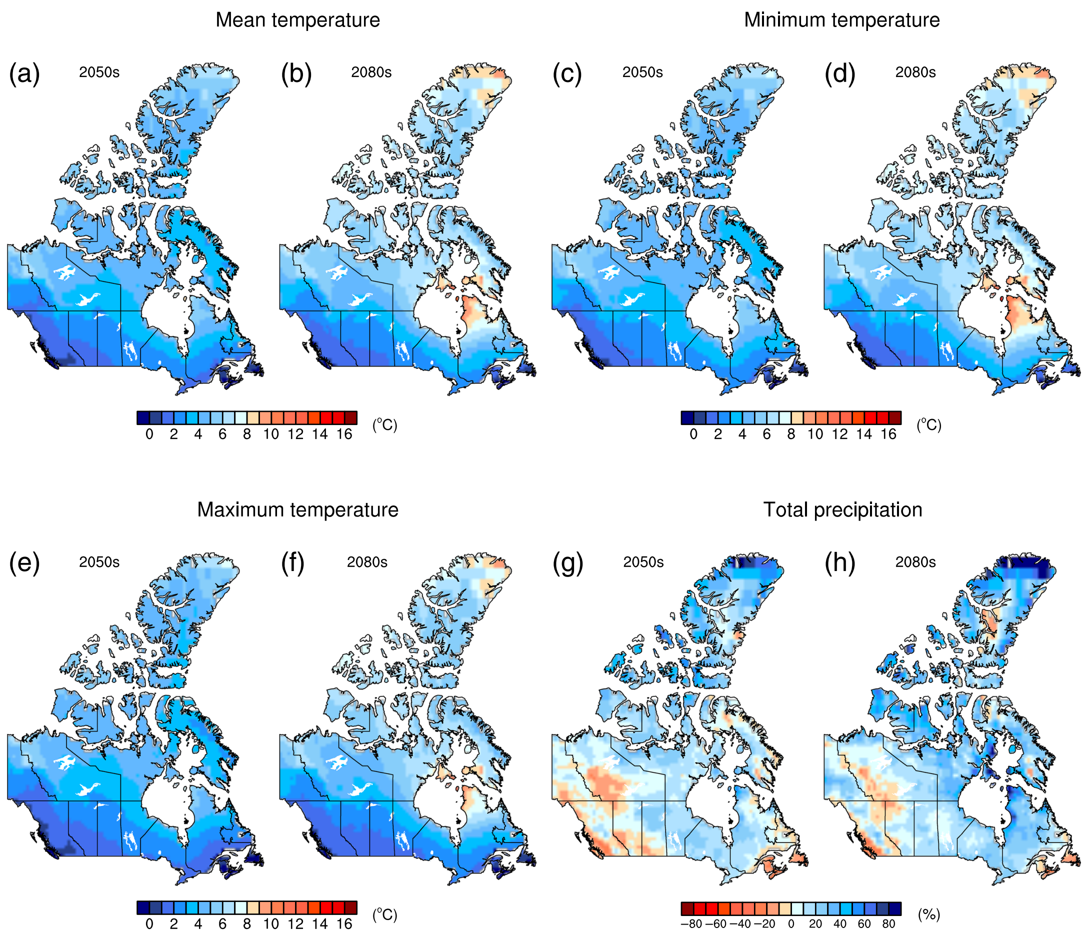

Figure 10. Spatial distributions of projected changes in winter (i.e. December, January and February) (a–f) temperature and (g,h) precipitation for the (a,c,e,g) 2050s and (b,d,f,h) 2080s under RCP4.5. [Colour figure can be viewed at wileyonlinelibrary.com].

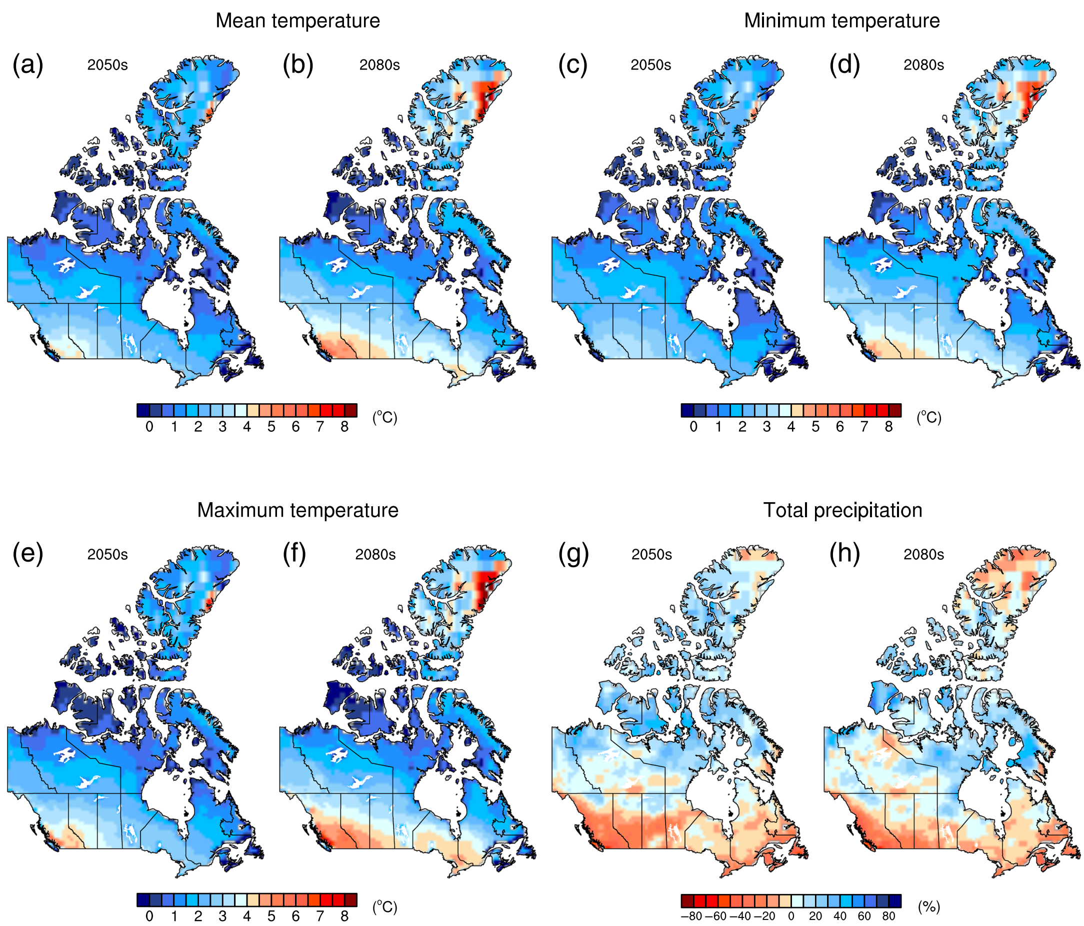

Figure 11. Spatial distributions of projected changes in summer (i.e. June, July and August) (a–f) temperature and (g,h) precipitation for the (a,c,e,g) 2050s and (b,d,f,h) 2080s under RCP4.5. [Colour figure can be viewed at wileyonlinelibrary.com].

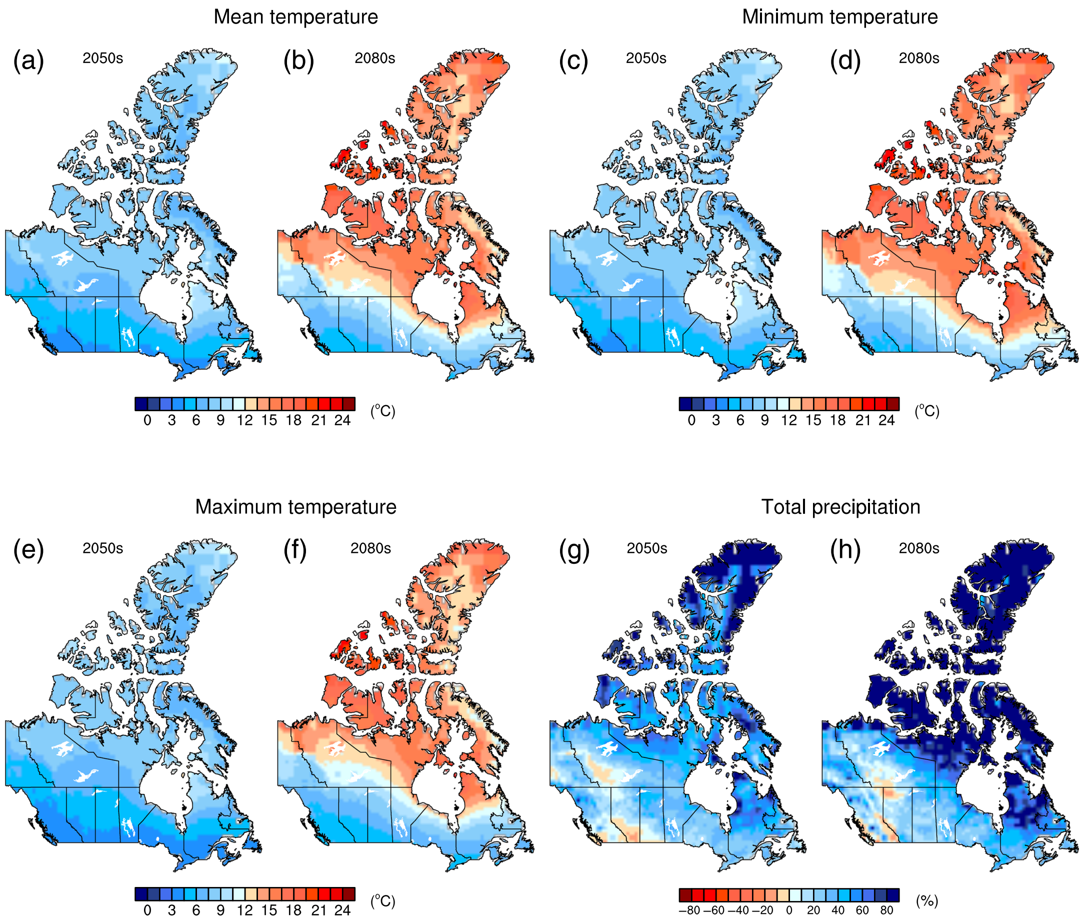

Figure 12. Spatial distributions of projected changes in winter (i.e. December, January and February) (a–f) temperature and (g,h) precipitation for the (a,c,e,g) 2050s and (b,d,f,h) 2080s under RCP8.5. [Colour figure can be viewed at wileyonlinelibrary.com].

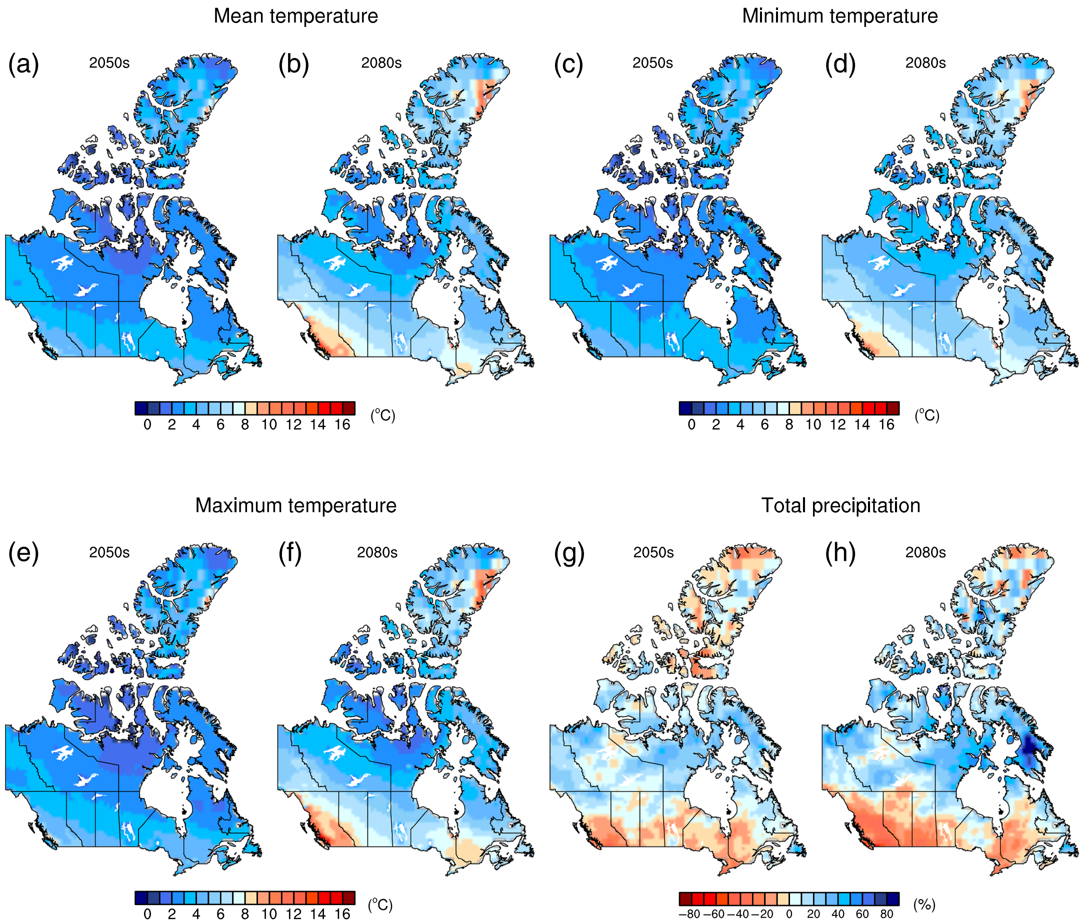

Figure 13. Spatial distributions of projected changes in summer (i.e. June, July and August) (a–f) temperature and (g,h) precipitation for the (a,c,e,g) 2050s and (b,d,f,h) 2080s under RCP8.5. [Colour figure can be viewed at wileyonlinelibrary.com].

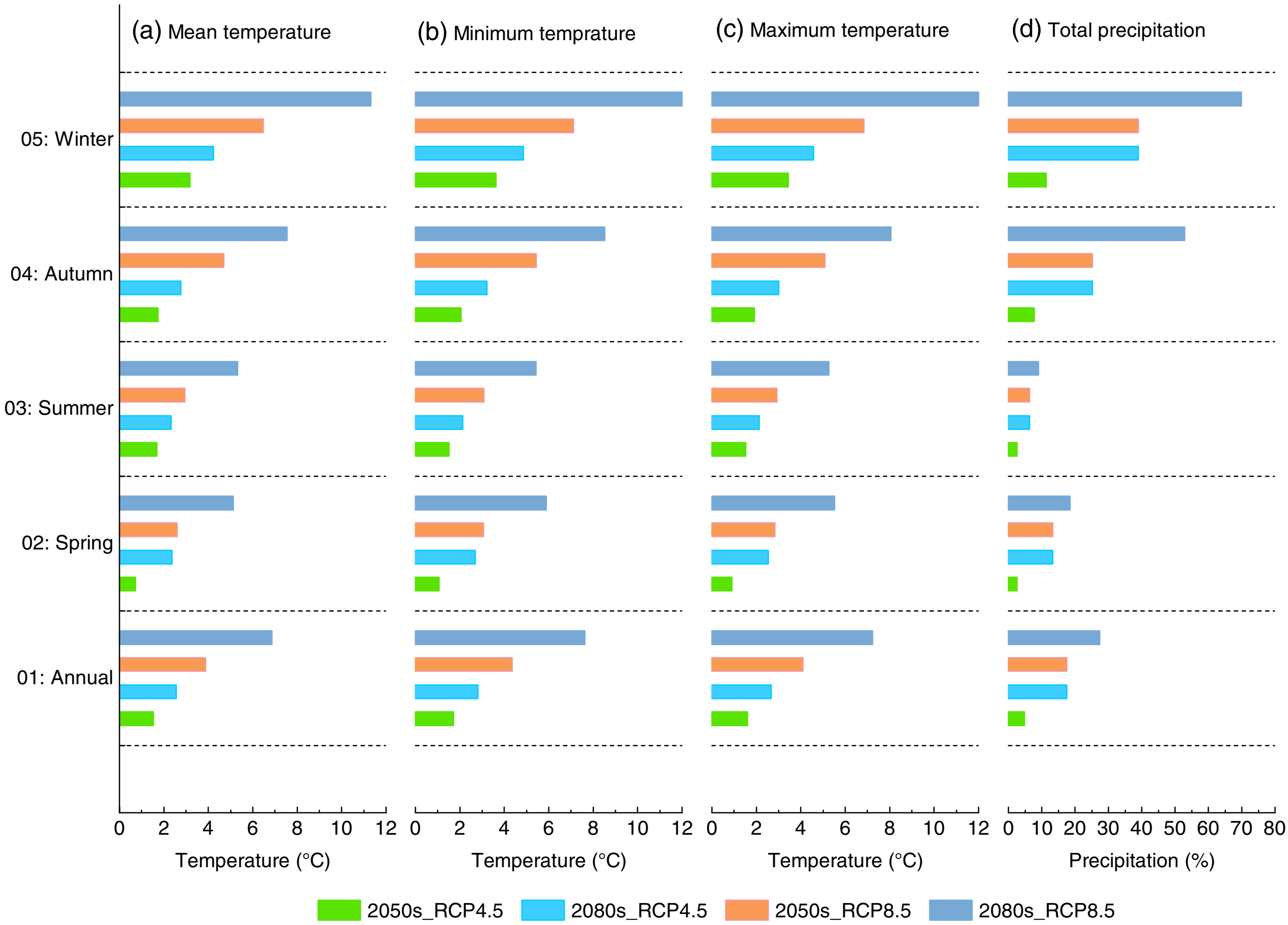

Figure 14. Projected changes in average seasonal and annual (a–c) temperature and (d) precipitation over the Canadian domain for the two future time periods. [Colour figure can be viewed at wileyonlinelibrary.com].

Figure 9 presents the spatial changes in the temperature and precipitation frequencies over the Canadian domain between the future periods and the baseline period for RCP4.5 and RCP8.5. In general, the PRECIS simulations under RCP4.5 and RCP8.5 reduce the frequencies of cold mean temperatures below −12 °C in the 2050s and 2080s. For example, the frequency changes in mean temperature in the 2050s under RCP4.5 are projected to decrease by 157 grid cells between −24 and −20 °C, 337 grid cells between −20 and −16 °C, and 194 grid cells between −16 and −12 °C. However, the frequencies of warm mean temperatures above 4 °C in the 2050s and 2080s are projected to increase, especially under the RCP8.5 scenario. For example, the projected changes in frequencies to the mean temperature in the 2080s under RCP8.5 is increased by 294 grid cells between 4 and 8 °C, 1389 grid cells between 8 and 12 °C, and 359 grid cells between 12 and 16 °C. In addition, the frequency changes in minimum and maximum temperature are similar to those of mean temperature, which are that the frequencies of warm temperatures above 4 °C are projected to increase and cold temperatures below 12 °C will decrease, except for the changes in frequency to T_{min} between −16 and −12 °C under RCP8.5. Furthermore, the results in Figure 9 also indicate that the PRECIS simulations show a decrease in the frequency of total precipitation under 400 mm, but an increase in the frequency above 400 mm. An increasing frequency pattern is found except for a slight decrease in precipitation between 1000 and 1400 mm under RCP4.5.

Figures 10–13 provide projected changes in T_{mean}, T_{max}, T_{min} and total precipitation for both winter and summer in the periods of the 2050s and 2080s under two RCPs. It is indicated that substantial inter-model variability is found. For example, PRECIS projects a larger increase in the three temperature variables in winter than in summer for the 2050s and 2080s. For the mean temperature in summer in the 2080s under RCP4.5, the largest increase over the Canadian domain is expected to be 9.4 °C. Nevertheless, the mean temperature is projected to be a maximum increase of 13.4 °C in winter in the 2080s under RCP4.5. More importantly, larger areas of Canada are projected to decrease more for precipitation in summer than in winter. Winter precipitation will increase more in the study area for two RCPs. For instance, the total precipitation in winter for the 2050s under RCP4.5 leads to an increase by as much as 80%, while the largest increase in summer precipitation is 59%. Based on the results presented in Figures 12, 13, it can be observed that the spatial patterns of changes in T_{mean}, T_{max}, T_{min} and total precipitation for both winter and summer in the 2050s and 2080s under RCP8.5 are similar to those found under RCP4.5. However, unlike RCP4.5, the magnitude of changes is significantly different. This indicates that the projected changes in temperature and precipitation variables will be intensified under RCP8.5 due to greater GHG concentrations. For example, winter mean temperature under RCP8.5 shows a significant increase by as much as 12 °C in the 2050s, while the highest increase under RCP4.5 is projected to be 8 °C in the same future period.

Figure 14 depicts projected changes in average annual temperature and precipitation variables over the entirety of Canada for two future periods under both scenarios. The results of the PRECIS simulation under two RCPs indicate that the largest increases in temperature variables are projected in winter than in any other season in the 2050s and 2080s under both RCP4.5 and RCP8.5. For example, the change in average annual mean temperature (i.e. T_{mean}) in the winter under RCP4.5 is projected to be 3.4 °C in the 2050s. However, the projected changes in average annual mean temperature in autumn, summer and spring in the 2050s under RCP4.5 will be 1.9, 1.5 and 0.9 °C, respectively. Likewise, there is a more significant increasing trend in winter for total precipitation over the Canadian domain. For

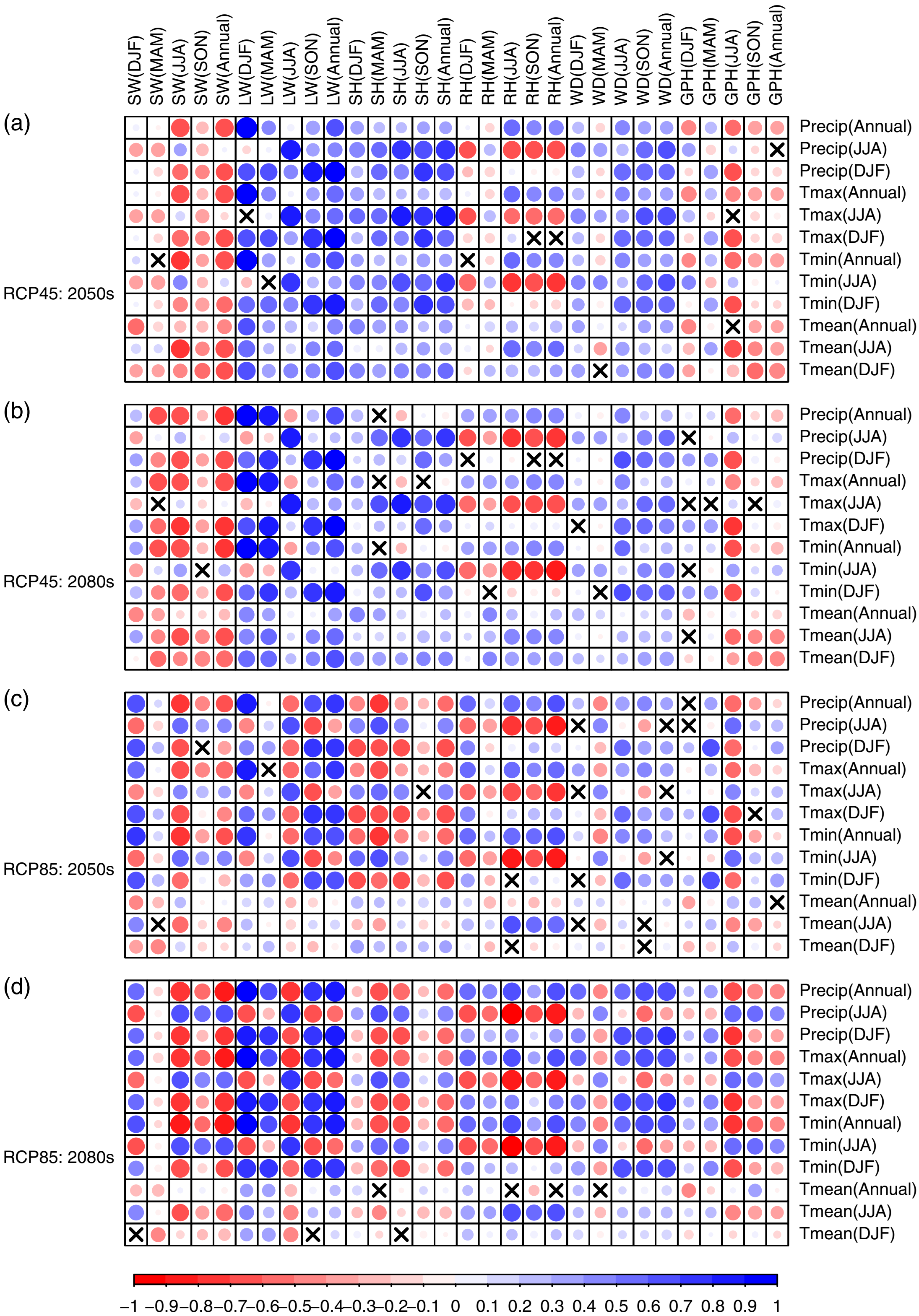

Figure 15. (a–d) Pearson correlation coefficients between the projected changes and climate factors including seasonal and annual total downward surface long-wave flux (LW), total downward surface short-wave flux (SW), relative humidity (RH), specific humidity (SH), wind speed (WD), geopotential height at 850 hPa (GPH). The correlations with a cross mark are considered to be insignificant since p-values are larger than 0.05. [Colour figure can be viewed at wileyonlinelibrary.com].

instance, the total precipitation in the 2050s under RCP4.5 will be increased by 11.27% in the winter, 7.61% in the autumn, 2.59% in the spring, and 2.64% in the summer. Similar patterns for the projected changes in average temperature and precipitation variables under RCP8.5 are found, based on the projected seasonal changes.

In general, the spatial patterns of the projected changes in temperature and precipitation variables are projected to be larger increases in winter compared with summer, and at higher latitudes compared with lower latitudes. Such patterns in projected changes are largely a consequence of natural variability in the real or simulated climate system (Deser *et al.*, 2012). They described that larger levels of natural variability are found in winter and at higher latitudes (Deser *et al.*, 2012). The results also indicated that the ranges from the smallest value to the largest value of the projected changes over the entirety of Canada are augmented from the 2050s to the 2080s. This implies that climate change for the 2080s is more unpredictable than the 2050s due to more uncertainties, and thus requires more comprehensive understanding and knowledge of the climate system and its natural variability (Deser *et al.*, 2012; Wang *et al.*, 2015b). In the meantime, it is indicated that only one model realization might not be sufficient to provide

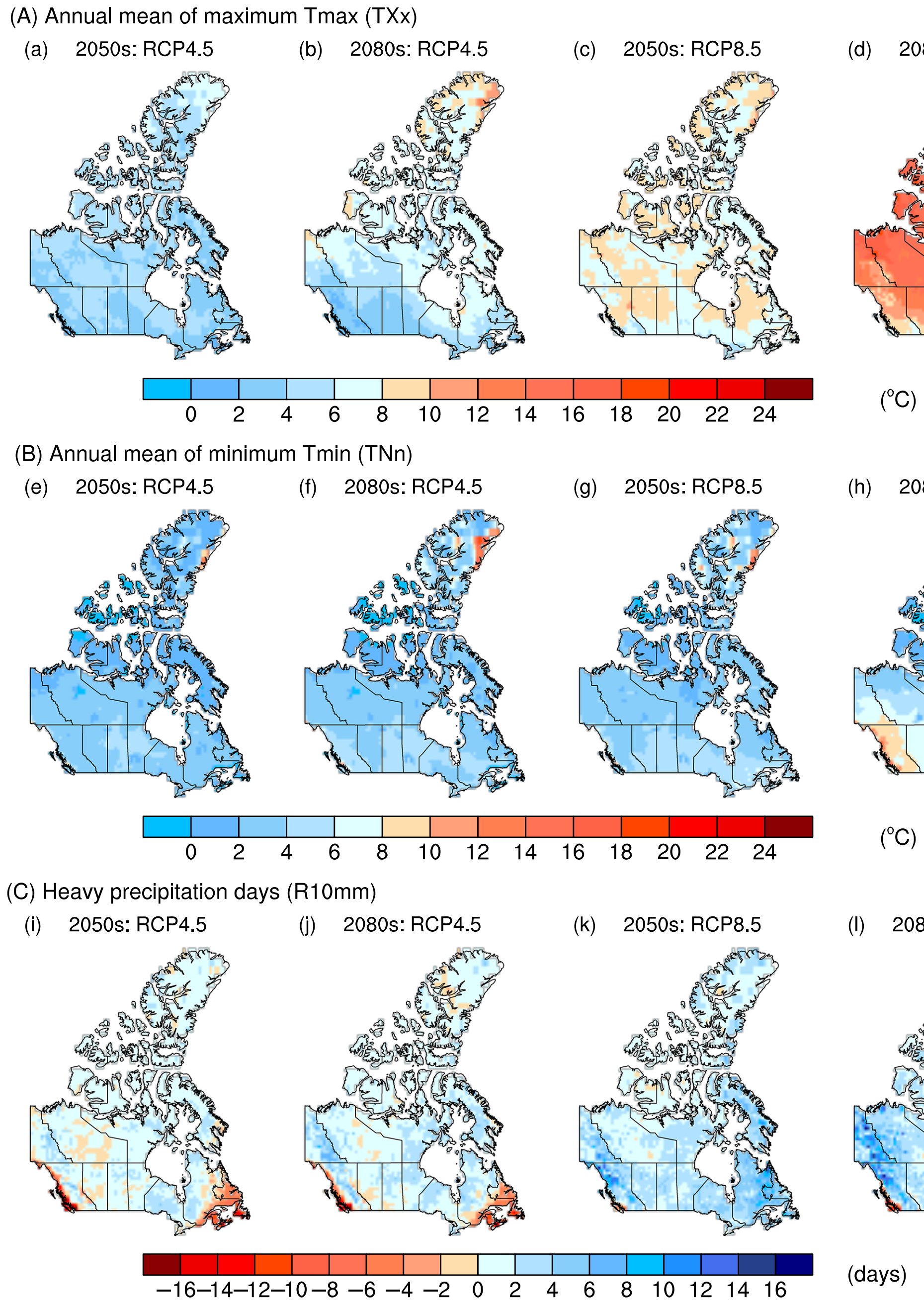

Figure 16. Spatial distributions of projected changes in (A,B) temperature and (C) precipitation extremes for the (a,c,e,g,i,k) 2050s and (b,d,f,h,j,l) 2080s under RCPs. [Colour figure can be viewed at wileyonlinelibrary.com].

a reliable climate projection subject to uncertainties owing to natural variability.

In order to analyse the mechanism that governed the projected changes in temperature and precipitation variables, total downward surface long-wave flux, total downward surface short-wave flux, wind speed, specific humidity, relative humidity and geopotential height at 850 hPa are further extracted for the future periods under RCPs. The Pearson correlation analysis method is employed to gain insight into atmospheric and terrestrial processes related to the projected changes. Figure 15 presents the Pearson correlation coefficients between the projected changes and climate factors. In general, all the three temperature variables are positively correlated with total downward surface long-wave flux (LW). It is also implied that the projected increases in surface temperature variables are mainly contributed from larger total downward surface long-wave flux, which would result in more outgoing long-wave radiation from the surface. The precipitation shows positive correlation with specific humidity and wind speed, which can be employed to calculate the water vapour flux. This implies that the projected changes in precipitation would mainly result from larger intensity of water vapour content transporting through a unit area (i.e. water vapour flux). These results are also consistent with previous studies (O'Gorman and Schneider, 2009; Qin and Xie, 2016).

In addition, we have calculated three extreme indices (i.e. TNn, TXx and R10mm). They are derived from the Expert Team on Climate Change Detection and Indices (ETCCDI: Frich *et al.*, 2002; Sillmann *et al.*, 2013). TNn (minimum of T_{min}) and TXx (maximum of T_{max}) describe the coldest and hottest day of a year, while R10mm (number of days where precipitation is large than 10 mm) represents heavy precipitation days (Frich *et al.*, 2002; Sillmann *et al.*, 2013). Figure 16 presents spatial distributions of the projected changes in temperature and precipitation extremes for the 2050s and 2080s under RCPs. It is indicated that the averages of the projected TNn (Figure 16(A)) would be generally increased from the 2050s to the end of this century under RCPs. As shown in Figure 16(B), the projected changes in TXx show a similarly increasing pattern. However, the magnitudes of the projected changes in TXx are slightly smaller than in TNn over Canada for two future periods under RCPs. As for R10mm (Figure 16(B)), the Had-PRECIS simulation projects a significant increase over the majority of Canada under RCPs for the 2050s and 2080s. However, R10mm would be projected to decrease in southwestern and southeastern Canada under RCP4.5 for the two future periods, while only small areas in southwestern Canada show a decreasing pattern under RCP8.5.

4. Conclusions

In this study, high-resolution projections of changes in temperatures and precipitation as well as their extreme indices over Canada were developed through the PRECIS model under RCP4.5 and RCP8.5. The PRECIS model was employed to conduct simulations for the historical period over the entirety of Canada, driven by the boundary conditions from both ERA-Interim (1979–2011) and HadGEM2-ES (1959–2005). The performance of the PRECIS simulations was then validated through comparison with observed temperature and precipitation over the baseline period (1986–2005). Future climate projections of temperature and precipitation as well as their extreme indices over two time-slices (i.e. the 2050s and 2080s) were extracted and analysed. The results could help explore how the regional climate over Canada will respond to global warming as well as the spatio-temporal characteristics of plausible climate changes in the Canadian context.

Based on the analysis of spatial patterns in projected temperature and temperature under RCPs, significant changes in climatic conditions over Canada are anticipated in the upcoming decades. The projected temperature in the two future periods indicates that there is an apparent spatially increasing pattern over Canada. The PRECIS simulation under RCPs reduces the frequencies of cold mean temperatures below $-12\,^{\circ}$C, while it increases frequencies of warm mean temperatures above $4\,^{\circ}$C. Moreover, it was found that the PRECIS simulation tends to project smaller increases in temperature over the southwestern region compared to the northern area. Meanwhile, total precipitation is projected to increase over the majority of Canada under RCP4.5 in the 2050s and 2080s, while there is a significant increase over the entire region except for a small area in the southwest under RCP8.5. The results indicate that there will be a decrease in frequencies of total precipitation under 400 mm, but an increase in precipitation frequencies above 400 mm. Furthermore, the projected temperature extremes would be increased from the 2050s to the end of this century, while the magnitudes of the projected increases in TXx are slightly smaller than in TNn. However, R10mm would be projected to decrease in southwestern and southeastern Canada under RCP4.5, while only small areas in the southwest show a decreasing pattern under RCP8.5.

This article presents a regional modelling approach for assessing projected climate change impacts over Canada. The validation results demonstrate that the PRECIS model can be an effective tool in reproducing historical climatological patterns of annual temperature (mean, maximum and minimum temperature) and total precipitation across Canada. The projected changes derived in this study will be useful to evaluate detailed regional impacts on economic, social and environmental sectors. Explorations and implications can also be employed for various climate change adaptation planning purposes. Analysis of the mechanisms governing the projected changes in temperature and precipitation variables over Canada can help understand atmospheric and terrestrial processes at regional and local scales. Dynamically downscaling different GCMs to address uncertainties owing to natural variability would deserve more future research effort.

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