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Regional scenarios of change over Canada: future climate projections

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Abstract

This analysis documents projected changes in daily precipitation and temperature characteristics over Canada based on a 15-member ensemble which had been downscaled using the Canadian Regional Climate Model—CanRCM4 at 50 km resolution by the Canadian Centre for Climate Modelling and Analysis (CCCma) under Representative Concentration Pathway (RCP) 8.5. In this study, the historical CanRCM4 simulations are first compared against observations for validation purposes. Then, a multivariate bias correction algorithm is applied to the CanRCM4 outputs to adjust the data against the EU WATCH Forcing Data ERA-Interim reanalysis (WFDEI). We analyze changes in mean and extremes for two 30-year non-overlapping future periods: 2021–2050 and 2071–2100 relative to 1979–2008. The results indicate that daily mean precipitation is projected to increase over Canada, with larger increases expected in the 2080s. However, decreases are projected in summer precipitation over the Canadian Prairies by the year 2100. Mean air temperature is projected to intensify towards the northern high latitude regions, particularly in the winter season. Precipitation and temperature extreme events may increase more than the mean. By examining the behavior of precipitation distribution tails, the mean of the probability distributions of wet extremes over the Saskatchewan (SRB) and Mackenzie River basins (MRB) is projected to shift to the right with global warming. For temperature extremes, minimum temperature may warm faster compared to daily maximum temperatures, particularly in the winter and towards the Arctic region.

Keywords: Canada; climate projections; precipitation; temperature; extremes

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1 Introduction

Findings of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2013) as well as the IPCC Special Report on Global Warming of 1.5°C (Huppmann et al., 2018) demonstrate that increases in anthropogenic greenhouse gases (GHGs) are accelerating the rate of global warming. Associated with a warmer climate are changes over space and time in the characteristics of extreme events such as floods and droughts (Sillmann et al., 2013a;Kharin et al., 2013;Betts et al., 2018). Given the social, economic and ecosystem impacts of these extremes, it is important to provide scale-relevant projections of expected changes in the behavior of these events in order to identify and formulate suitable strategies for water resources systems adaptation and risk management (Kundzewicz et al., 2017;Wilby and Dessai, 2010;Wilby, 2017;IPCC, 2013).

The water cycle is closely linked to the climate system. Small, sometimes insignificant variations in climate often lead to significant changes in hydrological processes. In particular, water resources in cold regions are stored mostly in the form of snowpacks and glaciers and have been found to be sensitive to small changes in air temperature. For example, most of the flows in western Canadian rivers rely on headwater supplies from the Rocky Mountains, which make up an important part of the regional and global hydrologic cycle (Pomeroy et al., 2016;Pederson et al., 2011). Given that these high elevation regions are also characterized by a cold region hydro-climate which is seasonally dependent, many existing studies suggest that climate variability and change would be most pronounced in these snow-dominated regions with negative consequences on seasonal and long-term water supplies anticipated (Stocker et al., 2013;Demaria et al., 2016;Islam et al., 2017).

Ongoing science hints at the intensification of the hydrologic cycle given the past warming trends which have resulted in significant changes in the hydrological regimes of many North American river basins (DeBeer et al., 2016;Coopersmith et al., 2014;Dumanski et al., 2015;Das et al., 2009). Observational records already indicate that a shift in stream hydrographs (Burn, 1994), and in extreme temperature and

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precipitation regimes (Vincent et al., 2015;Asong et al., 2016b) have occurred. For the cryosphere, changes in snow and ice regimes—reducing snow cover extent, glacier retreat, thawing of permafrost, and earlier breakup of seasonal freshwater ice cover are occurring as the warming trend continues (IPCC, 2013;Woo and Pomeroy, 2011;Woo et al., 1992). Enhanced warming is projected to alter the proportion of precipitation falling in the form of snow and rain, with a declining proportion arriving in the form of snow. Snow pack levels are also expected to form later in the winter, accumulate in smaller quantities, and melt earlier in the season, leading to reduced summer flows (Musselman et al., 2018). The greatest deficits are expected to occur in the summer, thus, decreased soil moisture levels and more frequent and severe droughts are anticipated (Mann and Gleick, 2015;Gleick, 2014;Allen et al., 2010;Arnell, 2008;Li et al., 2009).

The foregoing indicates that water resources in cold regions, already stressed with the hazards of natural variability will likely face additional challenges under uncertain climate futures (Arnell, 1999;Bates et al., 2008). At the moment, climate projections are provided by Earth System Models (ESMs), potentially downscaled further with Regional Climate Models (RCMs). However, ESM outputs still cannot be directly applied at the local scale for impacts assessment due to their coarse horizontal resolution (Asong et al., 2016b;Maraun et al., 2017;Maraun et al., 2010). Although subject to many biases, climate change projections offer a glimpse into possible future water resource impacts and challenges. To reduce biases and overcome the scale mismatch between the ESM/RCM outputs and the desired scale for impact assessment, climate model outputs are often bias-corrected to historical observations (Maraun et al., 2017;Cannon, 2016;Volosciuk et al., 2017).

The goal of the current study, therefore, is to analyze future changes in precipitation and temperature characteristics over Canada. These are key variables which govern hydrological cycle dynamics and are of paramount importance to hydrological processes in a changing climate. To this end, a 15-member ensemble under Representative Concentration Pathway (RCP) 8.5, downscaled by the

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Canadian Centre for Climate Modelling and Analysis (CCCma) as part of the Canadian Sea Ice and Snow Evolution Network (CanSISE) Climate Change and Atmospheric Research (CCAR) Network project, is utilized in this study. As mentioned above, these outputs often contain biases, thus, a multivariate quantile mapping approach is first applied to bias-correct the climate model simulations against the European Union Integrated Project Water and Global Change (WATCH) ERA-Interim reanalysis (WFDEI) at 3h × 0.5° resolution. We investigate further the consequences on the projected climate change signals of applying bias correction to the raw climate model outputs.

The paper is organized as follows. The study area and data are described in section 2. In section 3, we provide the methodology for bias correction, calculation of climate indices, and how projected climate signals are computed both for the mean and extreme states. The results and discussion are presented in section 4 and 5, respectively, while a summary of the main findings and conclusions are presented in section 6.

2 Study area and data sets

2.1 Study area

The case study (Fig. 1) includes the Canada continental domain south of latitude 72° N. This region contains major river basins such as the Great Lakes and St. Lawrence River systems, which is one of the largest freshwater resources in North America and globally. This region also comprises two main natural systems—the Saskatchewan (SRB) and Mackenzie River basins (MRB) which are testbeds for the Changing Cold Regions Network—CCRN (http://www.ccrnetwork.ca/ , last access: 6 March 2019) large-scale hydrological modelling strategy. The Prairies of Canada are characterized by a highly varying climate and decreasing water resources. This region is also prone to droughts such those in 1988 and 1999–2005 (Asong et al., 2018), as well as damaging floods in 2011, 2013, and 2014 (Burn and Whitfield, 2017;Burn et al., 2016).

2.2 Gridded observations

In order to bias-correct the climate model outputs, gridded sub-daily retrospective meteorology that describe well the historical climate over Canada are required. Several gridded products exist over this region, including the Princeton (Sheffield et al., 2006), the North American Regional Reanalysis (Mesinger et al., 2006), WFDEI (Weedon et al., 2014), forecasts of the Global Environmental Multiscale(GEM) atmospheric model (Yeh et al., 2002), and the Canadian Precipitation Analysis—CaPA (Mahfouf et al., 2007) data sets. Wong et al. (2017) performed an inter-comparison of precipitation estimates from these products against observed station data over Canada. They found the CaPA and WFDEI products to have close agreement with station observations. Nevertheless, GEM-CaPA whch is available for the period 2004 – 2016 is not only too short for bias-correcting ESM climate, variables such as air temperature and specific humidity are issued at 40 m height (projected changes in temperature are often analyzed at 2 m height since this is the level that is most relevant to biophysical and huamn activities).

The WFDEI variables such as air temperature and specific humidity are issued at the surface and a comparative analysis against ground measurements shows that it outperforms other products in Canada and the United States (Chadburn et al., 2015;Wong et al., 2017;Park et al., 2016;Behnke et al., 2016;Sapiano and Arkin, 2009). Therefore, the 3-h × 0.5° WFDEI product (1979 – 2016) is used in this study. We utilize the Global Precipitation Climatology Centre product (GPCC) version of WFDEI (WFDEI-GPCC) data set which has improved precipitation estimates relative to the Climate Research Unit (CRU) based product—WFDEI-CRU (Weedon et al., 2014) when compared against ground observations in our domain of interest.

2.3 Regional climate model outputs

The climate projections utilized in this study are sourced from the Canadian Centre for Climate Modelling and Analysis (CCCma) and are available at www.cccma.ec.gc.ca/data/canrcm/CanRCM4 (last access: 6 March 2019). The simulations span the North American domain defined by the Coordinated

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Regional Climate Downscaling Experiment for North America (CORDEX) project (http://www.cordex.org/domains/region1-north-america/, last access: 24 April 2019) from 1950-2100. Scinocca et al. (2016) downscaled outputs from the Second Generation Canadian Earth System Model (CanESM2), using a new RCM, the CCCma Regional Climate Model (CanRCM4) under RCP4.5 and RCP8.5. The forcing data for the historical runs (1950 – 2005), and future (2006 – 2100) simulations of CanRCM4 are derived from CanESM2 following the Coupled Model Intercomparison Project Phase 5 (CMIP5) protocols. The CanRCM4 large ensemble which consists of 50 members were downscaled at 0.44° (50 km) and 0.22° (25 km) horizontal resolutions. This large ensemble is an extension of the CanESM2 simulations proposed by the Canadian Sea Ice and Snow Evolution Network (CanSISE) Climate Change and Atmospheric Research (CCAR) Network project (https://www.cansise.ca/, last access: 24 April 2019). For this study, we used 15 members of the 0.44 degrees resolution product at 1-h time step under RCP8.5. The choice of number of ensembles examined is based solely on public data availability at the time of this analysis. The seven climate variables required for driving the CCRN hydrological models and which are bias corrected in this study are listed in Table 1. Nonetheless, only projected changes in precipitation and air temperature are analyzed in this paper.

3 Methodology

3.1 Data processing and multivariate bias correction

In order to bias correct CanRCM4 outputs against WFDEI, both data sets must have the same temporal and spatial dimensions. Prior to bias-correction, the 1-h CanRCM4 estimates were aggregated to 3-h values for consistency with the WFDEI data. CanRCM4 was further re-gridded to match the WFDEI specifications using nearest neighbor interpolation as implemented in the Climate Data Operators software (https://code.mpimet.mpg.de/projects/cdo/ , last access: 23 November 2018). For bias correction which accounts for dependence between the different variables (Table 1), an image processing technique described in Cannon (2018) for multivariate bias correction (MBCn) of climate model outputs

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was utilized. Models are fitted to data for each calendar month across each pixel in the study area while preserving the dependence structure among variables. The historical data sets used in the fitting procedure include WFDEI (1979 – 2008) and CanRCM4 (1979 – 2008). Using the fitted models, we apply changes in quantiles to CanRCM4 output from 1950 – 2100.

3.2 Assessing changes in mean climate

In order to evaluate the projected climate change signals with respect to the reference period (1979–2008), two 30-year time windows (2021–2050 and 2071–2100) are studied. Using the 15-member ensemble, the climate change signal is investigated in terms of both the mean and extremes of precipitation and temperature. To investigate changes in mean climate, mean daily precipitation and temperature are computed for each ensemble member, and delta statistics are derived between the historical and future periods (delta statistics converted to relative percentage changes in the case of precipitation). The changes are derived for the time periods mentioned above: 2021–2050 (2030s) and 2071–2100 (2080s) with respect to 1979–2008 (1990s). The projected changes are computed by season: summer (JJA), autumn (SON), winter (DJF), and spring (MAM).

3.3 Assessing changes in climate extremes

Investigations of future changes in temperature and precipitation extremes have focused primarily on two approaches. The first is based on indices of climate extremes with return periods of about a year or less (e.g. extremely wet days, diurnal temperature range). The second method focuses on extreme value theory which is important for assessing the vulnerability of engineering infrastructure to climate change (Kharin et al., 2007;Asong et al., 2015;Coles et al., 2001). While climate extremes in a in a climate change context are often studied in these two ways, this study investigates changes in climate extremes using the first method which has a much broader context and can be useful for investigating the hydrologic and water resource implications of climate change (Sillmann et al., 2013b). A set of 27 indices focusing mainly on climate extremes has been made available by the Expert Team on Climate Change

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Detection and Indices—ETCCDI (http://etccdi.pacificclimate.org/list_27_indices.shtml , last access: 6 March 2019) (Karl et al., 1993;Karl and Easterling, 1999;Zhang et al., 2011). In the present study, the ETCCDI indices were computed as implemented in the Pacific Climate Impacts Consortium's "*climdex.pcic.ncdf*" package (http://pacificclimate.github.io/climdex.pcic.ncdf/, last access: 6 March 2019). The default thresholds prescribed in the package for computing these indices are used here. Where applicable, changes in the indices over the 2030s and 2080s are analyzed relative to the 1990s (see section 3.2 for details). The following water resource-relevant indices are further examined in this study: maximum 5−day Precipitation (RX5day); maximum 1−day Precipitation (RX1day); extremely wet days (R99p); monthly minimum value of daily minimum temperature (TNn); monthly maximum value of daily maximum temperature (TXx); and diurnal temperature range (DTR). Details on these indices are found in Sillmann et al. (2013b), Sillmann et al. (2013a), on the ETCCDI website as well as in the *climdex.pcic.ncdf* package manual.

4 Results

This section presents the results and a discussion of various analyses described in section 3. Assessment of CanRCM4 outputs against WFDEI and the performance of the MBCn algorithm is shown first followed by future changes in mean and extremes of precipitation and temperature. Raw CanRCM4 (CanRCM4_Raw) outputs are also discussed to assess the skill of MBCn in preserving the simulated climate change signals. We present the results in two dimensions: (1) temporal plots of areal averaged characteristics over the MRB and SRB for RCP8.5 from 1950 – 2100, (2) spatial patterns of simulated changes for the 2030s and 2080s, and (3) probability distributions that reveal the tail characteristics of seasonal precipitation indices over the MRB and SRB. For spatial changes, results are shown for the 15-member ensemble mean. Emphasis is placed on the unbiased (CanRCM4_Corr) CanRCM4 simulations while the impact of bias correction on the results is discussed in section 4.4 for both CanRCM4_Corr and CanRCM4_Raw.

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4.1 Evaluation and bias correction of climate variables

RCM outputs are known to contain biases that are mostly inherited from the driving ESM (Ehret et al., 2012;Laprise, 2008). Thus, we begin our analysis by showing why there is the need to bias-correct CanRCM4 output. For this purpose, threshold exceedance indices such as the days with precipitation > 1 mm (R1mm), and consecutive dry (CDD) and wet days (CWD) are computed from both WFDEI and 15 members of the CanRCM4 outputs (precipitation threshold = 1 mm) during 1979 – 2008. Figure 2a shows quantile-quantile plots of R1mm for the study domain. It is evident that CanRCM4 tends to underestimate the number of wet days. Concerning CDD and CWD averaged across longitudinal bands for the entire study domain, CanRCM4 overestimates CWD (Fig. S1a). However, CanRCM4 agrees well with WFDEI in terms of CDD except from latitude 60° poleward where CDD is underestimated by CanRCM4. It is worth mentioning that the performance of WFDEI north of 60° N is questionable given the paucity of observed meteorological data in these high latitude environments (Weedon et al., 2014;Beck et al., 2017).

Next, we assess whether the bias is removed after applying MBCn to the raw 3-h CanRCM4 outputs. Figure 2b depicts quantile-quantile plots of R1mm after bias correction. The MBCn algorithm shifts the distribution of CanRCM4 to match that of WFDEI although the number of wet days are slightly underestimated by MBCn. Note that R1mm is a derived quantity from the 3-h data (bias correction was performed at the 3-h resolution). The impact of bias correction on the wet-dry day physics produced by the climate model can be substantial and have been recognized as one of the reasons why bias correction should be applied with care (Ehret et al., 2012;Johnson and Sharma, 2012). Figure S2 shows the spatial patterns of 3-h precipitation averaged over the reference period (1979 – 2008) for the uncorrected (CanRCM4_Raw) and corrected (CanRCM4_Corr) simulations as well as the mean bias (CanRCM4_Corr–WFDEI). As shown in Fig. S2, the spatial patterns of precipitation between CanRCM4_Raw and CanRCM4_Corr are very similar since biases are corrected per grid point. The bias (CanRCM4_Corr – WFDEI) is very close to zero across the study domain, implying that MBCn was able to correct the statistical properties of CanRCM4 simulated precipitation amounts to match those of WFDEI. The same holds true in the case of air temperature (Fig. S3). This discussion is substantiated further in section 4.4.

4.2 Future projections of mean climate

4.2.1 Projected changes in daily precipitation

We begin this section by presenting results of the temporal evolution and projected spatial patterns of CanRCM4_Raw and CanRCM4_Corr climate. Figure 3 shows the time series of daily precipitation over the MRB and SRB as simulated by the 15-member CanRCM4 ensemble. Both the individual simulations as well the ensemble mean of the 15 realizations are shown. Over the MRB, compared to the historical period, mean precipitation may likely increase by the year 2100. Seasonally, the relative change is 15% (DJF), 15% (MAM), 14% (JJA), and 25% (SON) by the year 2100 based on the mean of 15 ensemble members. For the SRB, apart from a decrease in summer precipitation, the projections indicate that mean precipitation may increase in the future. Seasonally, the relative change is 20% (DJF), 19% (MAM), -6% (JJA), and 11% (SON) by the year 2100. In terms of variability, precipitation variability is higher over SRB compared to MRB as shown by the large inter-realization spread. Also, there is no noticeable difference between CanRCM4_Raw and CanRCM4_Corr daily precipitation.

Projected changes in the spatial and seasonal patterns of mean precipitation are depicted in Fig. 4. It is evident that the changes are seasonally dependent. CanRCM4 projects a likely increase in mean precipitation over most of the study area for all seasons. The increase may be greater in the 2080s compared to the 2030s. In the JJA, a large belt of the Canadian Prairies may expect a decrease in mean precipitation of about 15% by 2100 while eastern and northern regions may experience up to 80% increase in precipitation during the same season. Summaries of possible changes in precipitation over the MRB and SRB are presented in Table 2. Apart from a projected decrease (-1.5%) in mean precipitation during the JJA over SRB in the 2080s, both basins may experience an increase in precipitation in the 2030s and

2080s. Larger changes are projected for the SRB compared to the MRB, particularly in the MAM, DJF and SON in the 2080s.

4.2.2 Projected changes in daily mean temperature

The temporal evolution of daily mean temperature averaged over the MRB and SRB as simulated by the 15-member CanRCM4 ensemble is shown in Fig. 5. Both the individual simulations as well the ensemble mean of the 15 realizations are shown. Over the MRB, compared to the historical period, mean temperature may increase by the end of the 21st century. Seasonally, an increase in air temperature of ~2.5°C by the year 2100 based on the mean of 15 ensemble members is projected for all seasons and river basins. The projections further indicate not only warming conditions, but air temperature in DJF and MAM will likely be more variable compared to JJA and SON.

For mean air temperature (Fig. 6), relative to the 1990s, a projected increase on seasonal and annual time scales over the study area is expected for the future periods. The warming will likely intensify in the 2080s compared to the 2030s. Spatially, most of the warming will probably occur over the artic region where mean temperature of ~10°C is projected by 2100. Seasonally, higher warming is simulated for the DJF season both in the 2030s and 2080s. Although mean temperature is projected to increase for the whole domain in JJA, most of the warming will likely concentrate on the Prairies, over the Rocky Mountains, and most of southern British Columbia in the 2080s. Table 3 summarizes changes in mean temperature for the MRB and SRB. The DJF season may experience the most warming of about 8.6°C over the MRB during the 2080s. However, the case is different for the SRB where the most warming of 7.2°C is projected in the JJA during the 2080s. In general, larger changes in temperature are projected for other seasons (apart from JJA) over the MRB compared to the SRB. The MRB is a located north of the SRB, thus the south-north spatial warming trend projected for the whole domain corroborates this finding.

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4.3 Future projections of climate extremes

4.3.1 Precipitation extremes

Projected changes in selected precipitation indices (RX5day, R99p, and RX1day) are presented here. Changes in the spatial patterns of maximum 5-day precipitation (RX5day) are illustrated in Fig. 7. As expected, the spatial structure of changes in RX5day is similar to that of mean precipitation (Fig. 4). Relative to the 1990s, CanRCM4 projects an increase (>100%) in RX5day over most of Canada in DJF, MAM, JJA, and SON, with higher increases in the 2080s compared to the 2030s. Using the 2080s as an example, increases in RX5day may be greater in DJF over most of the Prairies and the Arctic region. However, in JJA, the spatial patterns of changes are different compared to DJF. Decreases in RX5day of about -30% are projected for the Prairies in JJA in the 2080s. On a river basin scale, summaries of projected changes in RX5day over the MRB and SRB are presented in Table 4 for all four seasons. Over the MRB (SRB), RX5day is projected to increase by 30.6 (46.7) %, 45.5 (52.6) %, and 39.5 (32.3) % in DJF, MAM, and SON, respectively, by the year 2100. However, in JJA, RX5day is projected to increase by 15.6% over the MRB while a decrease of -1.7% is projected for the SRB in the 2080s.

Figure 8 displays changes in extremely wet days (R99p) during the 2030s and 2080s. Compared to the historical period, R99p is projected to almost double (~180%) by the 2080s. Spatially, increases of up to 140% are projected over the eastern and western parts of Canada by 2100. However, patches of small (<15%) or no change (0%) in R99p are projected for the southern and central regions (e.g. the Prairies) of the study domain. Furthermore, changes in the characteristics of precipitation extremes in a future climate were examined by plotting the probability distributions (PDFs) of seasonal maximum 1-day precipitation (RX1day) averaged over the MRB and SRB (Fig. 9). For the PDFs, across the MRB and SRB, larger tails are projected for the JJA compared to other seasons, and more so for the 2080s. RX1day is projected to shift (i.e. change in the mean) to the right with global warming (Table S1). In the MRB, relative to the 1990s, changes in the mean of RX1day in the 2030s (2080s) are 14.3 (32.6%), 15.5 (42.2%), 7.4

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(12.8%), and 16.3 (43.0%) for DJF, MAM, JJA, and SON, respectively. Similarly, for the SRB, mean changes for RX1day in the 2030s (2080s) are 16.9 (47.2%), 20.2 (48.9%), 2.4 (-5.4%), and 17.0 (34.0%) for DJF, MAM, JJA, and SON, respectively.

4.3.2 Temperature extremes

Temperature extremes are examined here in terms of spatial and seasonal patterns of TNn, TXx and DTR. The projected mean changes of TNn, TXx and DTR as simulated by the CanRCM4 15-member ensemble are shown in Fig. 10 for the 2080s. Noticeably, TNn (Fig. 10a) increases more than TXx (Fig. 10b). Also, TNn and TXx show dissimilar spatial and seasonal patterns. TNn shows clear distinct spatial and seasonal patterns compared to TXx. Particularly, TNn amplifies in the northern regions than in the southern latitudes. Seasonally, changes in TNn of more than 15°C are projected for the DJF season across much of Canada. The least changes (<3°C) in TNn are projected for the warm season (JJA).

Apart from TNn and TXx, changes in the DTR were analyzed since DTR is a useful index of global climate change. Using observational records, it has been found that DTR has decreased significantly since the year 1950 because of differential changes in minimum and maximum temperatures. There is much debate surrounding the evaluation of DTR in current observational datasets and the capabilities of ESMs to represent its characteristics in a future climate (Thorne et al., 2016;You et al., 2017;Lewis and Karoly, 2013;Braganza et al., 2004). Figure 10c shows changes in DTR in the 2080s relative to the 1990s. There is a projected decrease (up to -3°C) in DTR in the DJF and MAM seasons for most of Canada. In the JJA, DTR is projected to increase (~2.5°C) over much of western Canada. In the SON and on an annual scale (ANN), DTR is projected to decrease more uniformly over the study area.

Basin-scale summaries of changes in TNn, TXx and DTR over the MRB and SRB for the 2080s are shown in Table 5. In the MRB, relative to the 1990s, the largest (smallest) projected increase in TNn of 9.4°C (6.1 °C) is in DJF (JJA). For TXx, the largest (smallest) increase 6.2°C (3.3 °C) is in JJA (MAM). For DTR, decreases are projected for DJF (-1.2°C), MAM (-1.4°C) and SON (-0.8°C), while an increase is projected for

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the JJA (0.1°C). Similarly, In the SRB, relative to the 1990s, the largest (smallest) projected increase in TNn of 9.3°C (6.1 °C) is in DJF (MAM). For TXx, the largest (smallest) increase 7.2°C (2.7 °C) is in JJA (DJF). And for DTR, decreases are projected for DJF (-1.9°C), MAM (-1.1°C) and SON (-0.5°C), while an increase is projected for the JJA (0.4°C). In both basins, the change in TNn (TXx) is greater in DJF (JJA) compared to other seasons. This in turn explains the projected decrease (increase) in DTR during these seasons.

4.4 Impact of bias correction on the simulated climate change signals

This section discusses the impact that bias correction has on the CanRCM4_Raw outputs. Whether bias correction should be applied to climate model outputs remains a contentious issue in the climate change impacts community for many reasons (Ehret et al., 2012). Also, raw climate model outputs include systematic biases that affect the climate change signals of high-impact meteorological fields such as precipitation and temperature. Throughout the paper, we have shown results for both CanRCM4_Raw and CanRCM4_Corr. Here, we investigate whether the simulated climate change signal was preserved after applying MBCn to the CanRCM4_Raw outputs. The temporal plots in Figs. 3 and 5 clearly indicate that MBCn can preserve precisely the inter-annual variability of precipitation and temperature as simulated by the CanRCM4. Fig. 11 shows the impact of bias correction on the seasonal cycle of daily mean precipitation and temperature over the MRB and SRB. Firstly, there is a large wet bias in CanRCM4_Raw precipitation particularly in MAM, JJA and SON, and a warm bias in temperature, particularly during winter (DJF) relative to WFDEI averaged over the MRB and SRB. This also necessitated the application of MBCn on the raw CanRCM4 outputs. By comparing the CanRCM4 historical (1990s) simulations against WFDEI, it is clear that MBCn removes satisfactorily the bias in the CanRCM4_Raw outputs.

On the projected climate signal, there is both a projected change in the amplitude of precipitation as well as a shift in the phase of the cycle over the MRB with global warming. In the 1990s and 2030s, peak precipitation occurs in July, however, by the 2080s, the precipitation peak is projected to occur in June. Although CanRCM4 projects wetter conditions in a warmer climate for the SRB, no noticeable change in the phase of the cycle with global warming is anticipated. This is also true for the annual cycle of mean temperature over MRB and SRB where warmer air temperatures are projected throughout the year by 2100. These climate change signals are very well preserved after applying MBCn to the CanRCM4_Raw outputs. It is worth stating that future research needs are on developing process-based bias correction methods that depend on simulated intensities rather than preserving the raw climate change signal from climate models (Ivanov et al., 2018;Maraun et al., 2017).

5 Discussion

The foregoing analyses have indicated that mean precipitation and temperature will likely increase over Canada, especially by the end of the 21st century. Nevertheless, the projected changes are seasonally and regionally dependent. For example, over the SRB (MRB), a decrease (increase) in mean precipitation is projected in the JJA by the year 2100. Regarding spatial patterns of warming, there is a general south-north heating trend with the polar (arctic) regions projected to warm the most under RCP8.5. With regard to wet and warm extremes, the derived climate indices will probably increase more than the mean. Another interesting dynamic is that regions affected by smaller changes in the mean also tend to have the smallest projected changes in the magnitude of extremes, and vice versa. The SRB is projected to get drier in the JJA, accompanied with a decrease in wet extremes. However, mean and extreme temperature are projected to likely increase over this basin. This points to a possible intensification of meteorological drought over this river basin in a warmer climate.

By comparing the bias-corrected (CanRCM4_Corr) climate signals against the raw outputs (CanRCM4_Raw), CanRCM4_Raw overestimates the amplitude of the seasonal cycle of projected precipitation and temperature (Fig. 11) although temperature well reproduced compared to precipitation. The comparison does not only aid in assessing the skill of the CanRCM4 in reproducing observed historical climate but also illustrates the need for bias-correcting CanRCM4 outputs against WFDEI. Whether or not bias correction algorithms should be applied to ESM outputs is a subject of much debate. However,

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systematic biases (as highlighted above) and fitness for purpose, such as the need to drive cold regions hydrologic models which require high resolution inputs (Willkofer et al., 2018;Wood et al., 2004) necessitated the current exercise. As mentioned previously, the results discussed here are based on outputs from one RCM. However, the CMIP5 ensemble has a large spread and conclusions based on one climate model should be interpreted with caution.

The results discussed in this study are certainly in line with existing literature. For projected changes in mean climate, the IPCC AR5 findings indicate that "high latitudes are *very likely* to experience greater amounts of precipitation due to the increased specific humidity of the warmer troposphere as well as increased transport of water vapor from the tropics by the end of this century under the RCP8.5 scenario." Kharin et al. (2007) and Sillmann et al. (2013a) found a probable increase in precipitation and temperature extremes over North America using a multi-model ensemble approach. Nevertheless, the above studies were done on annual scales. But, our findings using downscaled CanESM2 outputs agree (regarding the direction of change) with such previous analyses which investigated future changes in precipitation and temperature characteristics at coarse scale.

At the regional scale, several studies have been carried out using RCMs which still operate at horizontal resolutions larger than 20 km to investigate future changes in climate over Canada. For example, Wang et al. (2015) used the PRECIS RCM to generate a large ensemble climate simulations over Ontario, Canada, between1950 to 2099, forced at the boundary by perturbed physics from the HadCM3 ensemble under the SRES A1B emissions scenario. They found a tendency towards a warming trend over the study region in the range of 2.6-2.7°C in the 2030s, and 5.9-7.4°C in the 2080s. Similarly, they found an increase in annual total precipitation of 4.5-7.1% during the 2030s and 3.2- 17.5% for the 2080s. In terms of temperature extremes, Jeong et al. (2016) analyzed future changes in hot events over Canada by analyzing eleven RCM outputs from the North American Regional Climate Change Assessment Program (NARCCAP), under the A2 emission scenario. Their results suggested a likely intensification in the frequency of hot days. Nevertheless, the projected changes showed high spatial variability and were highly dependent on the RCM and parent GCM combination. For precipitation extremes, Monette et al. (2012) investigated changes in single- and multi-day events as simulated by six RCMs from the NARCCAP ensemble. They found a projected increase to various return levels for multiple Northeast Canadian watersheds during the future (2041–2070) period relative to the historical (1971–2000) period.

An analysis of changes in precipitation and temperature characteristics have also been carried out based upon high-resolution RCM projections at the 10 km scale. Erler et al. (2015) and Erler and Peltier (2016) analyzed changes in climate extremes in western Canada based upon an ensemble of high-resolution regional climate projections dynamically downscaled to 10 km resolution with the aid of the Weather Research and Forecasting (WRF) model in two different configurations with convection parameterized in the model. The simulations were performed for three 15-yr periods: a historical period from 1979 – 1994, a midcentury period from 2045 – 2060, and an end-century period from 2085 – 2100 under RCP 8.5. They found that changes in wet extremes generally followed projected changes in the mean, although the likely changes in mean and extreme precipitation differed strongly across seasons and regions. Furthermore, the projections showed an increase in DJF precipitation during the 2050s, whereas net precipitation in summer is projected to decrease as a result of increased evapotranspiration.

Generally, irrespective of horizontal resolution, previous studies agree in terms of the trend in air temperature with global warming. Although coarse resolution models (e.g. GCMs) project an increase in seasonal precipitation over Canada, the 10 km WRF simulations discussed above indicate a potential decrease in JJA precipitation over western Canada. However, wet extremes are projected to intensity at the same time albeit the CanRCM4 ensemble investigated here indicate a likely decrease in maximum 5-day precipitation (RX5day) in JJA over the Canadian Prairies.

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6 Summary and conclusions

Future changes in daily precipitation and temperature characteristics over Canada are documented in this study as part of the Changing Cold Regions Network (CCRN) future scenarios of change initiative. For this purpose, relevant climate variables were obtained from CCCma. Outputs from CanESM2 have been downscaled dynamically by using the CCCma Regional Climate Model (CanRCM4) at 0.44° (50 km) horizontal resolution under RCP8.5. After evaluating the CanRCM4 data against observations, substantial biases were found. Therefore, a multivariate bias correction algorithm was applied to the climate model outputs to adjust the data against a gridded climate product (WFDEI). Subsequently, we investigated whether the raw climate change signals were preserved after applying bias correction to the original data. Changes in mean climate and extremes are computed for two 30-year non-overlapping future periods: 2021–2050 (2030s) and 2071–2100 (2080s) relative to 1979–2008 (1990s), and for four seasons: DJF, MAM, JJA and SON as well as on an annual (ANN) basis. Based on these analyses, the most important findings of our study include:

(1) In terms of the temporal evolution, mean precipitation may increase over the MRB by the end of the 21st century. On a seasonal basis, higher increases are projected for the SON, DJF, MAM, and JJA, respectively. Over the SRB, apart from a likely decrease in JJA precipitation, increases in mean precipitation are projected for DJF, MAM and SON, respectively by the year 2100. Spatially, the projections indicate an increase in precipitation over most of Canada, with larger increases expected in the 2080s. However, decreases are projected for the southwestern parts of the United States in the DJF and MAM. In the JJA, a large belt of the Canadian Prairies may expect a decrease in mean precipitation by the end of the 21st century. Apart from a projected decrease in precipitation for the JJA over the SRB, both basins may experience an increase in precipitation in the 2030s and 2080s.

(2) Relative to the historical period, mean air temperature over Canada is projected to intensify with increasing radiative forcing in the future. Temporally, the areal averaged time series over MRB and

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SRB indicate that air temperature in DJF and MAM will likely be more variable compared to JJA and SON. The spatial patterns of changes in mean temperature show strong increases in the northern high latitude regions, particularly in the DJF season. On a river basin scale, the DJF season may experience the most warming of about 8.6°C over the MRB during the 2080s. However, the case is different for the SRB where the most warming of 7.2°C is projected in the JJA during the 2080s.

(3) Regarding wet and warm extremes, the examined climate indices are projected to increase more than the mean over the study area by the end of the 21st century. In terms of the probability distribution of extremes, across the MRB and SRB, larger tails are projected for the JJA compared to other seasons, and more so for the 2080s. For temperature extremes, TNn is projected to warm faster than TXx, particularly in the DJF and towards the poles. This in turn results in a projected decrease in DTR, implying that warmer air temperatures may prevail throughout the year in a warmer climate. Also, regions affected by smaller changes in the mean also tend to experience the smallest projected changes in the magnitude of extremes, and vice versa. The SRB is projected to get drier in the JJA, accompanied with a decrease in wet extremes. However, mean and extreme temperature are projected to likely increase over this basin.

(4) Compared to observations, the raw CanRCM4 outputs contained systematic biases which necessitated bias correction towards WFDEI. Throughout the paper, the impact of the climate change signal based on the uncorrected and corrected data have been discussed. We found a large difference between the climate indices computed from both data sets. For example, in Fig. 11, the climatological daily mean temperature over the MRB in July for CanRCM4_Raw in the 1990s is 18°C while the corrected one is ~13 °C. This results in a 5 °C warm bias which can have various consequences for hydrology and water resources management. Therefore, it was of paramount importance to evaluate CanRCM4 outputs for the presence of biases and correcting these outputs towards WFDEI prior to

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deriving the projected climate change signals shown here. Nonetheless, the WFDEI product is not perfect and caution should be exercised when interpreting these results.

(5) Finally, it is worth mentioning that the results presented in this study are in line with findings from the IPCC AR5. Furthermore, the analyses utilized outputs from only one global climate model (CanESM2) and one RCM (CanRCM4), however, there exist a large spread in the CMIP5 multi-model ensemble. This limitation can be overcome in future studies by evaluating additional RCM outputs from the CORDEX-NA larger ensemble. It is hoped that such efforts will strengthen further the findings of this study. While we did not explain the physical basis for the projected changes of precipitation and temperature documented here, it is recommended that future changes in temperature and precipitation characteristics be evaluated in relation to changes in atmospheric circulation patterns, and feedback mechanisms such as snow cover changes, soil moisture, and vegetation dynamics.

Competing interests

The authors declare that they have no conflict of interest.

Special issue statement

This article is part of the special issue “Understanding and predicting Earth system and hydrological change in cold regions”. It is not associated with a conference.

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Table 1: List of seven variables used for multivariate bias correction. The heights and units for each variable are shown

	WFDEI		CanRCM4	
Variable	**Height**	**Unit**	**Height**	**Unit**
Precipitation	Surface	kg m^{-2} s^{-1}	Surface	kg m^{-2} s^{-1}
Air Temperature	2 m	K	2 m	K
Specific Humidity	2 m	kg kg^{-1}	2 m	kg kg^{-1}
Wind Speed	10 m	m s^{-1}	10 m	m s^{-1}
Surface Pressure	Surface	Pa	Surface	Pa
Surface Downwelling Shortwave Radiation	Surface	W m^{-2}	Surface	W m^{-2}
Surface Downwelling Longwave Radiation	Surface	W m^{-2}	Surface	W m^{-2}

Table 2: Summary of projected changes (%) in daily mean precipitation for DJF, MAM, JJA, SON, and annual (ANN) scales during the 2021–2050 (2030s) and 2071–2100 (2080s) relative to 1979–2008 (1990s) over the Mackenzie (MRB) and Saskatchewan (SRB) River basins

	MRB				SRB			
	2030s		**2080s**		**2030s**		**2080s**	
	raw	*corr*	*raw*	*corr*	*raw*	*corr*	*raw*	*corr*
DJF	12.4	12.0	28.8	26.7	15.7	15.4	48.0	46.6
MAM	17.1	17.5	49.8	47.9	19.9	23.2	51.2	56.7
JJA	9.4	9.7	18.1	18.8	1.9	2.5	-1.8	-1.5
SON	17.0	18.1	41.9	42.9	18.2	20.7	38.8	42.9
ANN	12.9	13.7	30.5	31.7	10.3	12.8	22.5	27.9

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Table 3: Summary of projected changes (°C) in daily mean temperature. Other information is the same as in Table 2.

	MRB				SRB			
	2030s		2080s		2030s		2080s	
	raw	*corr*	*raw*	*corr*	*raw*	*corr*	*raw*	*corr*
DJF	3.3	3.3	8.5	8.6	2.6	2.6	6.4	6.4
MAM	1.9	1.9	5.1	5.2	1.5	1.5	4.2	4.2
JJA	2.4	2.4	6.1	6.1	2.8	2.7	7.2	7.2
SON	2.4	2.4	6.3	6.4	2.1	2.0	5.7	5.8
ANN	2.5	2.5	6.6	6.6	2.2	2.2	5.8	5.9

Table 4: Summary of projected changes (%) in maximum 5-day precipitation (RX5day) for DJF, MAM, JJA, and SON during the 2021–2050 (2030s) and 2071–2100 (2080s) relative to 1979–2008 (1990s) over the Mackenzie (MRB) and Saskatchewan (SRB) River basins

	MRB				SRB			
	2030s		2080s		2030s		2080s	
	raw	*corr*	*raw*	*corr*	*raw*	*corr*	*raw*	*corr*
DJF	11.2	12.6	31.1	30.6	17.5	16.2	51.7	46.7
MAM	16.1	16.5	41.4	45.5	24.2	21.4	51.7	52.6
JJA	10.0	8.1	16.4	15.6	3.6	3.2	-0.1	-1.7
SON	15.1	16.0	39.8	39.5	14.3	16.7	27.1	32.3

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Table 5: Summary of projected changes (°C) in monthly minimum of daily minimum temperature (TNn), monthly maximum of daily maximum temperature (TXx), and diurnal temperature range (DTR) for DJF, MAM, JJA, and SON during the 2071–2100 (2080s) relative to 1979–2008 (1990s) over the Mackenzie (MRB) and Saskatchewan (SRB) River basins.

	MRB						**SRB**					
	TXx		**TNn**		**DTR**		**TXx**		**TNn**		**DTR**	
	raw	*corr*	*raw*	*corr*	*raw*	*corr*	*raw*	*corr*	*raw*	*corr*	*raw*	*corr*
DJF	4.5	4.4	9.4	9.4	-1.2	-1.2	2.8	2.7	9.3	9.3	-1.7	-1.9
MAM	3.4	3.3	7.3	7.4	-1.0	-1.4	3.2	3.0	5.9	6.1	-0.9	-1.1
JJA	6.2	6.2	6.1	6.1	0.1	0.1	7.2	7.2	6.7	6.8	0.4	0.4
SON	5.0	4.9	8.1	8.2	-0.7	-0.8	5.2	5.1	6.6	6.7	-0.4	-0.5

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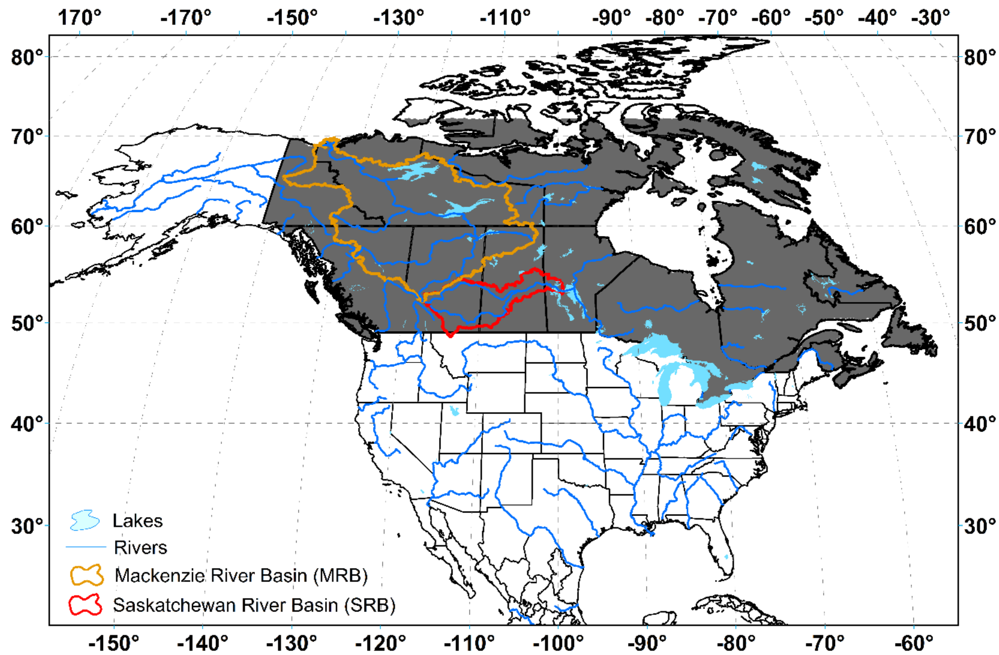

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558 **Figure 1:** Study area (grey shading) ranges from longitude 50° W to 150° W and latitude 30° N to 72° N.

559 The orange and red polygons indicate the Mackenzie and Saskatchewan River basins, respectively, which

560 are testbeds for the Changing Cold Regions Network large-scale hydrological modelling strategy.

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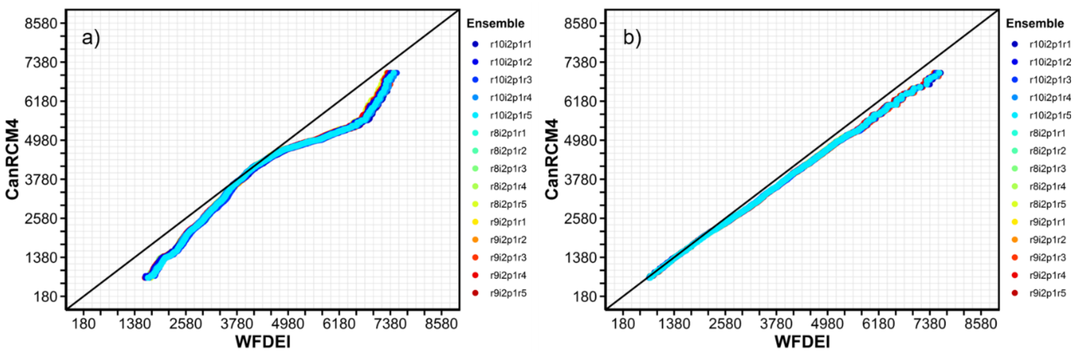

Figure 2: Quantile-quantile plots for days with >1 mm daily precipitation (R1mm) before (a) and after bias correction (b). All grid points over the domain are used. The color scale indicates the fifteen ensemble members utilized in this study.

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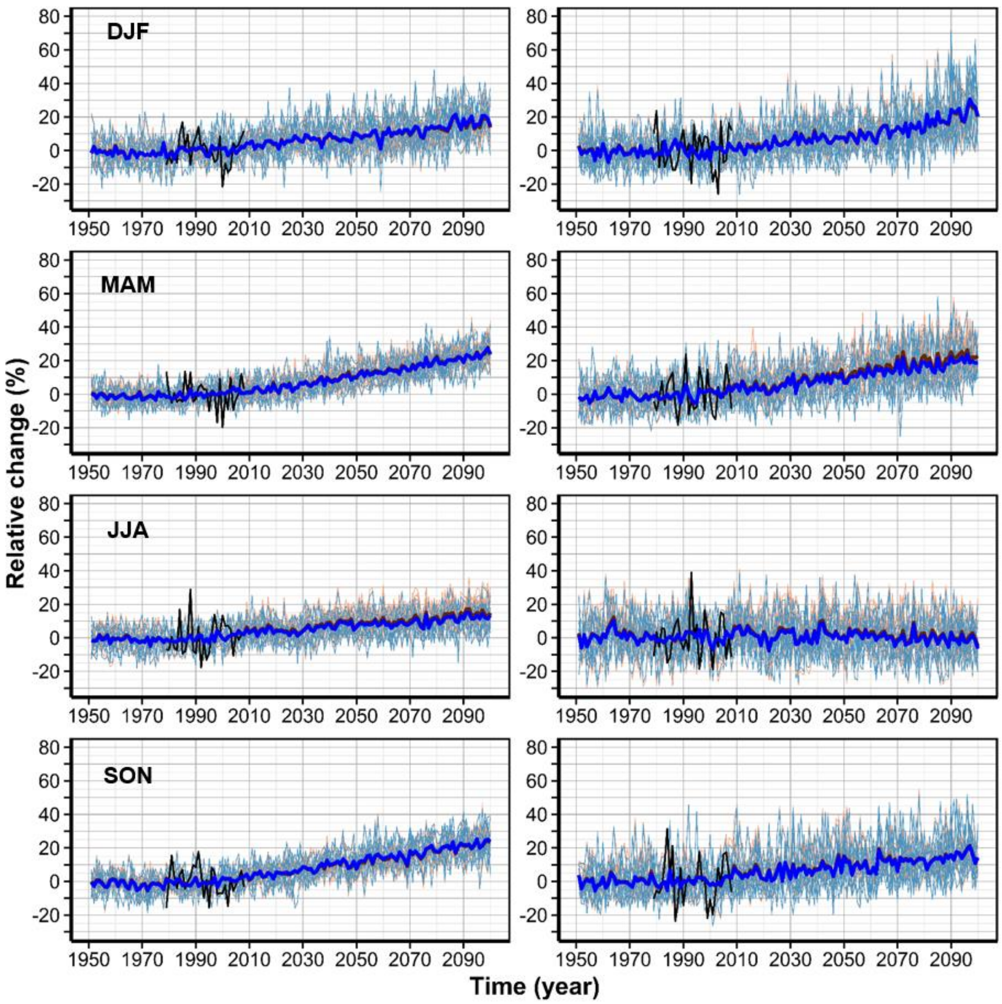

Figure 3: Temporal evolution (1950 – 2100) of basin-averaged mean daily precipitation for DJF, MAM, JJA, and SON. The anomalies are displayed relative to the reference period 1979–2008. Solid lines indicate the 15-member ensemble mean while the shading denotes the spread across ensemble members. Time series are shown for WFDEI (black), CanRCM4_Raw (red), and CanRCM4_Corr (blue) over the Mackenzie (left) and Saskatchewan (right) River basins.

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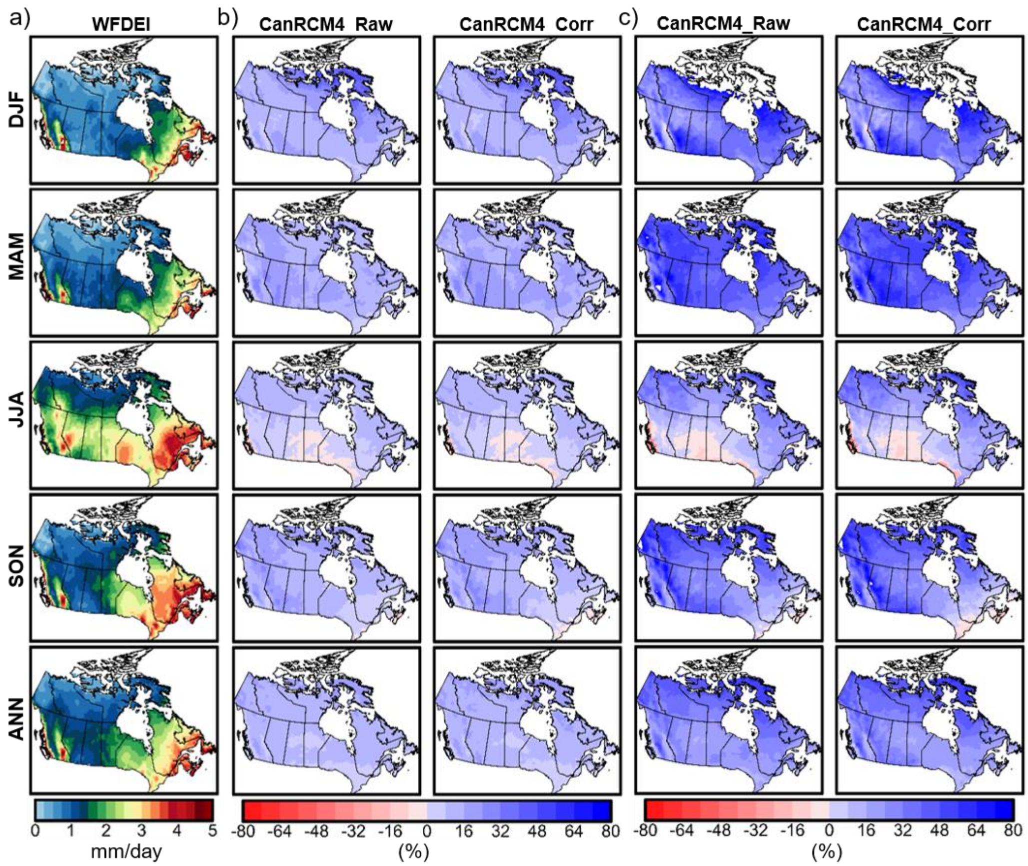

Figure 4: The multi-ensemble mean of climatologically averaged changes in daily mean precipitation (%) for DJF, MAM, JJA, SON, and annual (ANN) during the 2021–2050 (b) and 2071–2100 (c) future periods relative to 1979–2008. The spatial pattern of the observed WFDEI (a) product is also shown to aid in understanding future changes in the spatial variation of precipitation. The results are displayed both for the uncorrected (CanRCM4_Raw) and bias-corrected (CanRCM4_Corr) outputs.

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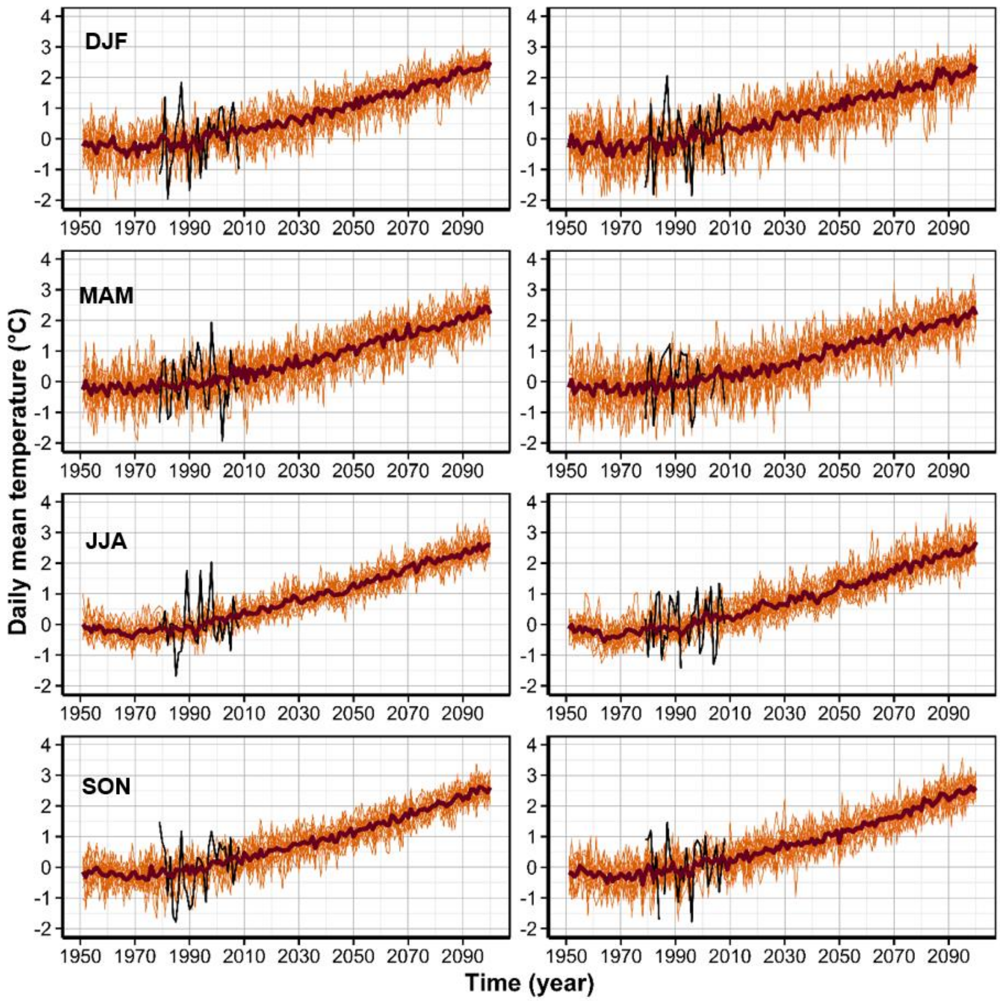

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592 **Figure 5:** Temporal evolution (1950 – 2100) of basin-averaged daily mean temperature for DJF, MAM, JJA,
593 and SON. The anomalies are displayed relative to the reference period 1979–2008. Solid lines indicate the
594 15-member ensemble mean while the shading denotes the spread across ensemble members. Time series
595 are shown for WFDEI (black), CanRCM4_Raw (red), and CanRCM4_Corr (blue) over the Mackenzie (left)
596 and Saskatchewan (right) River basins.

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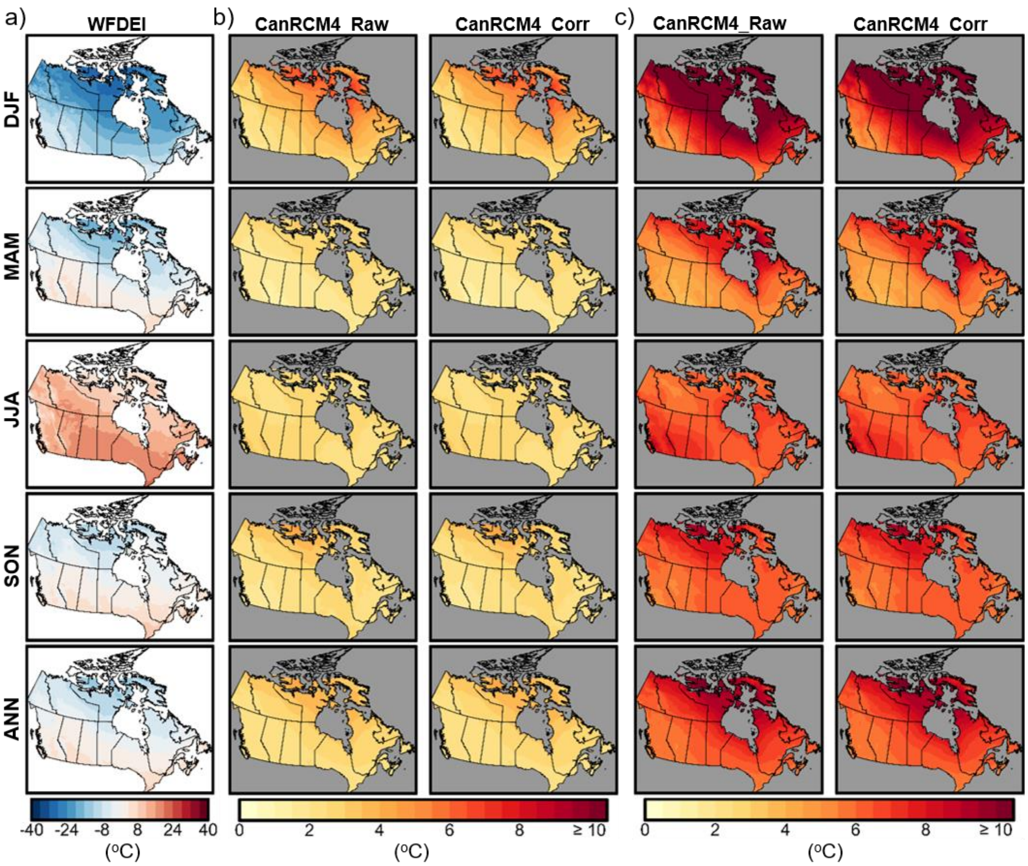

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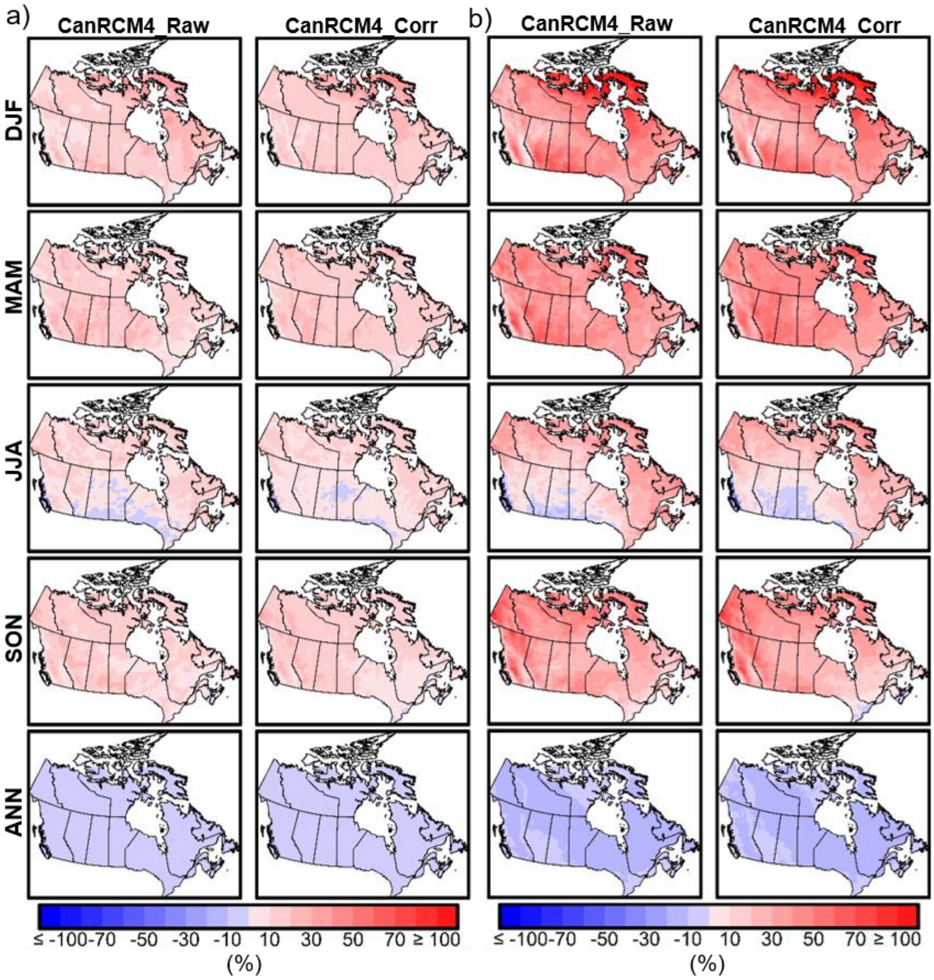

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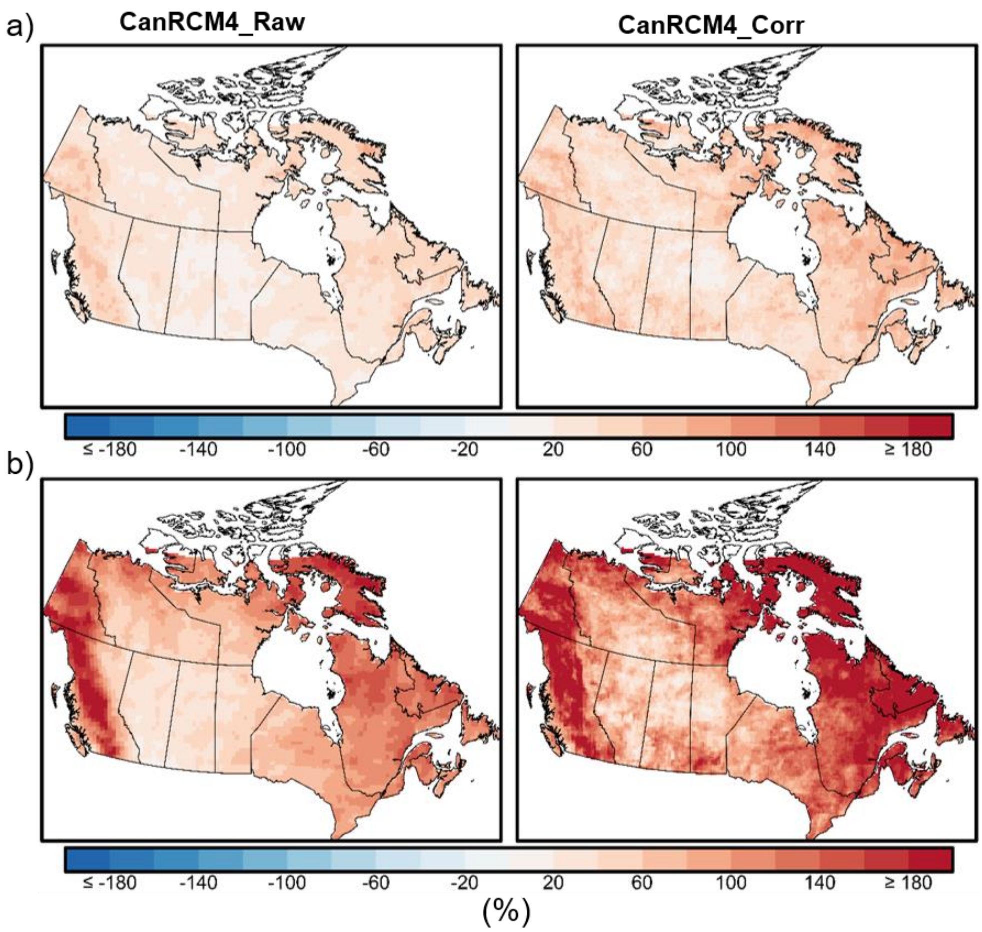
608 **Figure 7:** The ensemble mean of temporally averaged projected changes in maximum 5-day precipitation (RX5day) for DJF, MAM, JJA, SON, and annual (ANN) during the 2021–2050 (a) and 2071–2100 (b) future periods relative to 1979–2008. Other information is the same as in Fig. 4.



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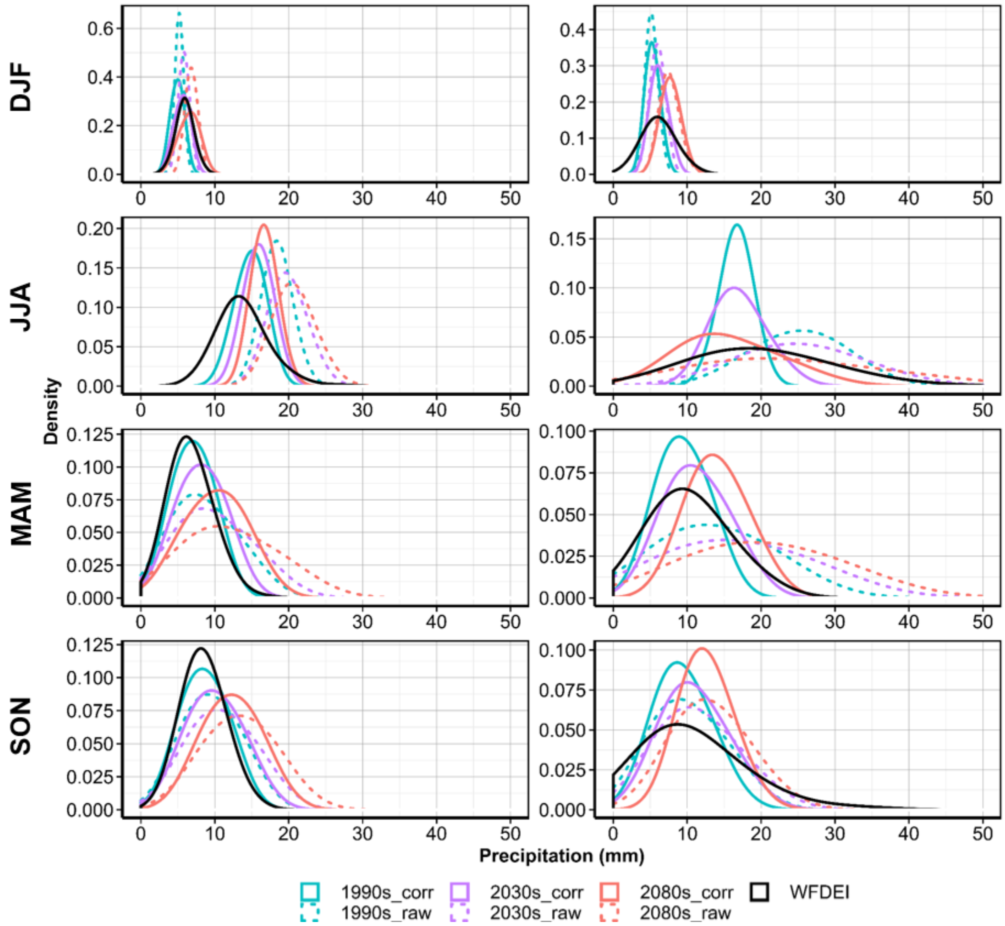
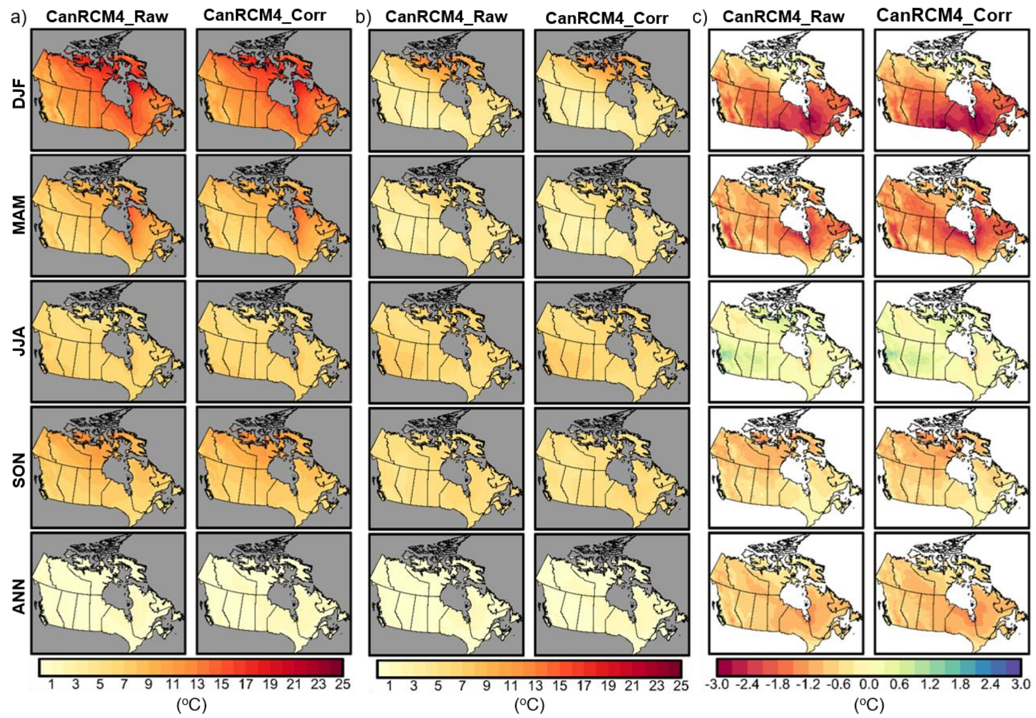


Figure 9: Probability distributions of seasonal maximum 1-day precipitation (RX1day) averaged over the Mackenzie (left) and Saskatchewan (right) River basins for DJF, MAM, JJA, and SON, during the historical (1979–2008) and two non-overlapping future periods (2021–2050 and 2071–2100). Results are shown for WFDEI, and both the uncorrected (dotted line) and bias-corrected (solid line) CanRCM4 outputs.

628 

629 **Figure 10:** The ensemble mean of temporally averaged projected changes in monthly minimum of daily

630 minimum temperature (a), monthly maximum of daily maximum temperature (b), and diurnal

631 temperature range (c). Changes are calculated for the DJF, MAM, JJA, and SON seasons, as well as for the

632 whole year (ANN) during the 2071–2100 future period as differences from the historical period (1979–

633 2008). Other information is the same as in Fig. 4.

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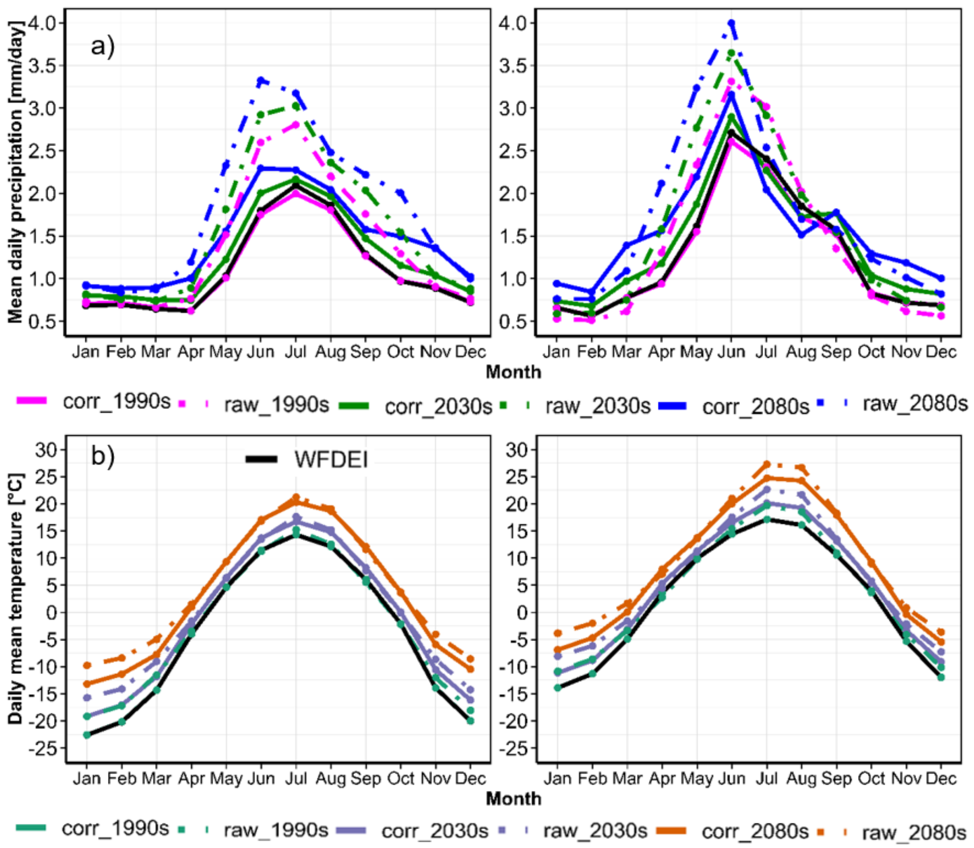

Figure 11: Seasonal cycle of mean daily precipitation (a) and daily mean temperature (b) for bias-corrected CanRCM4 (solid) and raw CanRCM4 outputs (dotted) over the Mackenzie (left) and Saskatchewan (right) River basins.

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References

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., and Hogg, E. T.: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests, Forest ecology and management, 259, 660-684, 2010.

Arnell, N.: Climate change and drought, Options Mediterannéenes, 2008.

Arnell, N. W.: Climate change and global water resources, Global environmental change, 9, S31-S49, 1999.

Asong, Z. E., Khaliq, M. N., and Wheater, H. S.: Regionalization of precipitation characteristics in the Canadian Prairie Provinces using large-scale atmospheric covariates and geophysical attributes, Stochastic Environmental Research and Risk Assessment, 29, 875-892, 10.1007/s00477-014-0918-z, 2015.

Asong, Z. E., Khaliq, M. N., and Wheater, H. S.: Projected changes in precipitation and temperature over the Canadian Prairie Provinces using the Generalized Linear Model statistical downscaling approach, Journal of Hydrology, 539, 429-446, http://dx.doi.org/10.1016/j.jhydrol.2016.05.044, 2016b.

Asong, Z. E., Wheater, H. S., Bonsal, B., Razavi, S., and Kurkute, S.: Historical drought patterns over Canada and their teleconnections with large-scale climate signals, Hydrol. Earth Syst. Sci., 22, 3105-3124, 10.5194/hess-22-3105-2018, 2018.

Bates, B., Kundzewicz, Z., and Wu, S.: Climate change and water, Intergovernmental Panel on Climate Change Secretariat, 2008.

Beck, H. E., Vergopolan, N., Pan, M., Levizzani, V., van Dijk, A. I., Weedon, G. P., Brocca, L., Pappenberger, F., Huffman, G. J., and Wood, E. F.: Global-scale evaluation of 22 precipitation datasets using gauge observations and hydrological modeling, Hydrology and Earth System Sciences, 21, 6201-6217, 2017.

Behnke, R., Vavrus, S., Allstadt, A., Albright, T., Thogmartin, W. E., and Radeloff, V. C.: Evaluation of downscaled, gridded climate data for the conterminous United States, Ecological Applications, 26, 1338-1351, doi:10.1002/15-1061, 2016.

Betts, R. A., Alfieri, L., Bradshaw, C., Caesar, J., Feyen, L., Friedlingstein, P., Gohar, L., Koutroulis, A., Lewis, K., Morfopoulos, C., Papadimitriou, L., Richardson, K. J., Tsanis, I., and Wyser, K.: Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5°C and 2°C global warming with a higher-resolution global climate model, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376, 20160452, doi:10.1098/rsta.2016.0452, 2018.

Braganza, K., Karoly, D. J., and Arblaster, J. M.: Diurnal temperature range as an index of global climate change during the twentieth century, Geophysical Research Letters, 31, doi:10.1029/2004GL019998, 2004.

Burn, D. H.: Hydrologic effects of climatic change in west-central Canada, Journal of Hydrology, 160, 53-70, https://doi.org/10.1016/0022-1694(94)90033-7, 1994.

Burn, D. H., Whitfield, P. H., and Sharif, M.: Identification of changes in floods and flood regimes in Canada using a peaks over threshold approach, Hydrological Processes, 30, 3303-3314, 10.1002/hyp.10861, 2016.

Burn, D. H., and Whitfield, P. H.: Changes in cold region flood regimes inferred from long-record reference gauging stations, Water Resources Research, 53, 2643-2658, 10.1002/2016wr020108, 2017.

Cannon, A. J.: Multivariate Bias Correction of Climate Model Output: Matching Marginal Distributions and Intervariable Dependence Structure, Journal of Climate, 29, 7045-7064, 10.1175/jcli-d-15-0679.1, 2016.

Cannon, A. J.: Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables, Climate Dynamics, 50, 31-49, 10.1007/s00382-017-3580-6, 2018.

Chadburn, S. E., Burke, E. J., Essery, R. L. H., Boike, J., Langer, M., Heikenfeld, M., Cox, P. M., and Friedlingstein, P.: Impact of model developments on present and future simulations of permafrost in a global land-surface model, The Cryosphere, 9, 1505-1521, 10.5194/tc-9-1505-2015, 2015.

Coles, S., Bawa, J., Trenner, L., and Dorazio, P.: An introduction to statistical modeling of extreme values, Springer, 2001.

Coopersmith, E. J., Minsker, B. S., and Sivapalan, M.: Patterns of regional hydroclimatic shifts: An analysis of changing hydrologic regimes, Water Resources Research, 50, 1960-1983, doi:10.1002/2012WR013320, 2014.

Das, T., Hidalgo, H. G., Pierce, D. W., Barnett, T. P., Dettinger, M. D., Cayan, D. R., Bonfils, C., Bala, G., and Mirin, A.: Structure and Detectability of Trends in Hydrological Measures over the Western United States, Journal of Hydrometeorology, 10, 871-892, 10.1175/2009jhm1095.1, 2009.

DeBeer, C. M., Wheater, H. S., Carey, S. K., and Chun, K. P.: Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: a review and synthesis, Hydrol. Earth Syst. Sci., 20, 1573-1598, 10.5194/hess-20-1573-2016, 2016.

Demaria, E. M. C., Roundy, J. K., Wi, S., and Palmer, R. N.: The Effects of Climate Change on Seasonal Snowpack and the Hydrology of the Northeastern and Upper Midwest United States, Journal of Climate, 29, 6527-6541, 10.1175/jcli-d-15-0632.1, 2016.

Dumanski, S., Pomeroy, J. W., and Westbrook, C. J.: Hydrological regime changes in a Canadian Prairie basin, Hydrological Processes, 29, 3893-3904, doi:10.1002/hyp.10567, 2015.

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., and Liebert, J.: HESS Opinions" Should we apply bias correction to global and regional climate model data?", Hydrology and Earth System Sciences, 16, 3391-3404, 2012.

Erler, A. R., Peltier, W. R., and D'Orgeville, M.: Dynamically Downscaled High-Resolution Hydroclimate Projections for Western Canada, Journal of Climate, 28, 423-450, 10.1175/jcli-d-14-00174.1, 2015.

Erler, A. R., and Peltier, W. R.: Projected Changes in Precipitation Extremes for Western Canada based on High-Resolution Regional Climate Simulations, Journal of Climate, 29, 8841-8863, 10.1175/jcli-d-15-0530.1, 2016.

Gleick, P. H.: Water, drought, climate change, and conflict in Syria, Weather, Climate, and Society, 6, 331-340, 2014.

Huppmann, D., Rogelj, J., Kriegler, E., Mundaca, L., Forster, P., Kobayashi, S., Séferian, R., and Vilariño, M. V.: Scenario analysis notebooks for the IPCC Special Report on Global Warming of 1.5°C, in, 2018.

IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp., 2013.

Islam, S. u., Déry, S. J., and Werner, A. T.: Future Climate Change Impacts on Snow and Water Resources of the Fraser River Basin, British Columbia, Journal of Hydrometeorology, 18, 473-496, 10.1175/jhm-d-16-0012.1, 2017.

Ivanov, M. A., Luterbacher, J., and Kotlarski, S.: Climate Model Biases and Modification of the Climate Change Signal by Intensity-Dependent Bias Correction, Journal of Climate, 31, 6591-6610, 10.1175/jcli-d-17-0765.1, 2018.

Jeong, D. I., Sushama, L., Diro, G. T., Khaliq, M. N., Beltrami, H., and Caya, D.: Projected changes to high temperature events for Canada based on a regional climate model ensemble, Climate Dynamics, 46, 3163-3180, 10.1007/s00382-015-2759-y, 2016.

Johnson, F., and Sharma, A.: A nesting model for bias correction of variability at multiple time scales in general circulation model precipitation simulations, Water Resources Research, 48, doi:10.1029/2011WR010464, 2012.

Karl, T. R., Jones, P. D., Knight, R. W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K. P., Lindseay, J., Charlson, R. J., and Peterson, T. C.: A new perspective on recent global warming: asymmetric trends of daily maximum and minimum temperature, Bulletin of the American Meteorological Society, 74, 1007-1024, 1993.

Karl, T. R., and Easterling, D. R.: Climate extremes: selected review and future research directions, Climatic change, 42, 309-325, 1999.

Kharin, V. V., Zwiers, F. W., Zhang, X., and Hegerl, G. C.: Changes in Temperature and Precipitation Extremes in the IPCC Ensemble of Global Coupled Model Simulations, Journal of Climate, 20, 1419-1444, 10.1175/jcli4066.1, 2007.

Kharin, V. V., Zwiers, F. W., Zhang, X., and Wehner, M.: Changes in temperature and precipitation extremes in the CMIP5 ensemble, Climatic Change, 119, 345-357, 10.1007/s10584-013-0705-8, 2013.

Kundzewicz, Z. W., Krysanova, V., Dankers, R., Hirabayashi, Y., Kanae, S., Hattermann, F. F., Huang, S., Milly, P. C. D., Stoffel, M., Driessen, P. P. J., Matczak, P., Quevauviller, P., and Schellnhuber, H. J.: Differences in flood hazard projections in Europe – their causes and consequences for decision making, Hydrological Sciences Journal, 62, 1-14, 10.1080/02626667.2016.1241398, 2017.

Laprise, R.: Regional climate modelling, Journal of Computational Physics, 227, 3641-3666, 2008.

Lewis, S. C., and Karoly, D. J.: Evaluation of Historical Diurnal Temperature Range Trends in CMIP5 Models, Journal of Climate, 26, 9077-9089, 10.1175/jcli-d-13-00032.1, 2013.

Li, Y., Ye, W., Wang, M., and Yan, X.: Climate change and drought: a risk assessment of crop-yield impacts, Climate research, 39, 31-46, 2009.

Mahfouf, J. F., Brasnett, B., and Gagnon, S.: A Canadian precipitation analysis (CaPA) project: Description and preliminary results, Atmosphere-Ocean, 45, 1-17, 10.3137/ao.v450101, 2007.

Mann, M. E., and Gleick, P. H.: Climate change and California drought in the 21st century, Proceedings of the National Academy of Sciences, 112, 3858-3859, 2015.

Maraun, D., Wetterhall, F., Ireson, A. M., Chandler, R. E., Kendon, E. J., Widmann, M., Brienen, S., Rust, H. W., Sauter, T., Themeßl, M., Venema, V. K. C., Chun, K. P., Goodess, C. M., Jones, R. G., Onof, C., Vrac, M., and Thiele-Eich, I.: Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user, Reviews of Geophysics, 48, doi:10.1029/2009RG000314, 2010.

Maraun, D., Shepherd, T. G., Widmann, M., Zappa, G., Walton, D., Gutiérrez, J. M., Hagemann, S., Richter, I., Soares, P. M. M., Hall, A., and Mearns, L. O.: Towards process-informed bias correction of climate change simulations, Nature Climate Change, 7, 764, 10.1038/nclimate3418, 2017.

Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P. C., Ebisuzaki, W., Jović, D., Woollen, J., Rogers, E., and Berbery, E. H.: North American regional reanalysis, Bulletin of the American Meteorological Society, 87, 343-360, 2006.

Monette, A., Sushama, L., Khaliq, M. N., Laprise, R., and Roy, R.: Projected changes to precipitation extremes for northeast Canadian watersheds using a multi-RCM ensemble, Journal of Geophysical Research: Atmospheres, 117, 10.1029/2012jd017543, 2012.

Musselman, K. N., Lehner, F., Ikeda, K., Clark, M. P., Prein, A. F., Liu, C., Barlage, M., and Rasmussen, R.: Projected increases and shifts in rain-on-snow flood risk over western North America, Nature Climate Change, 8, 808-812, 10.1038/s41558-018-0236-4, 2018.

Park, H., Yoshikawa, Y., Oshima, K., Kim, Y., Ngo-Duc, T., Kimball, J. S., and Yang, D.: Quantification of Warming Climate-Induced Changes in Terrestrial Arctic River Ice Thickness and Phenology, Journal of Climate, 29, 1733-1754, 10.1175/jcli-d-15-0569.1, 2016.

https://doi.org/10.5194/hess-2019-249
Preprint. Discussion started: 16 July 2019

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Discussions

Pederson, G. T., Gray, S. T., Ault, T., Marsh, W., Fagre, D. B., Bunn, A. G., Woodhouse, C. A., and Graumlich, L. J.: Climatic Controls on the Snowmelt Hydrology of the Northern Rocky Mountains, Journal of Climate, 24, 1666-1687, 10.1175/2010jcli3729.1, 2011.

Pomeroy, J. W., Fang, X., and Marks, D. G.: The cold rain-on-snow event of June 2013 in the Canadian Rockies — characteristics and diagnosis, Hydrological Processes, 30, 2899-2914, 10.1002/hyp.10905, 2016.

Sapiano, M. R. P., and Arkin, P. A.: An Intercomparison and Validation of High-Resolution Satellite Precipitation Estimates with 3-Hourly Gauge Data, Journal of Hydrometeorology, 10, 149-166, 10.1175/2008jhm1052.1, 2009.

Scinocca, J. F., Kharin, V. V., Jiao, Y., Qian, M. W., Lazare, M., Solheim, L., Flato, G. M., Biner, S., Desgagne, M., and Dugas, B.: Coordinated Global and Regional Climate Modeling, Journal of Climate, 29, 17-35, 10.1175/jcli-d-15-0161.1, 2016.

Sheffield, J., Goteti, G., and Wood, E. F.: Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling, Journal of Climate, 19, 3088-3111, 2006.

Sillmann, J., Kharin, V., Zwiers, F., Zhang, X., and Bronaugh, D.: Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections, Journal of Geophysical Research: Atmospheres, 118, 2473-2493, 2013a.

Sillmann, J., Kharin, V. V., Zhang, X., Zwiers, F. W., and Bronaugh, D.: Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate, Journal of Geophysical Research: Atmospheres, 118, 1716-1733, doi:10.1002/jgrd.50203, 2013b.

Stocker, T. F., Qin, D., Plattner, G.-K., Alexander, L. V., Allen, S. K., Bindoff, N. L., Bréon, F.-M., Church, J. A., Cubasch, U., Emori, S., Forster, P., Friedlingstein, P., Gillett, N., Gregory, J. M., Hartmann, D. L., Jansen, E., Kirtman, B., Knutti, R., Krishna Kumar, K., Lemke, P., Marotzke, J., Masson-Delmotte, V., Meehl, G. A., Mokhov, I. I., Piao, S., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell, D., Talley, L. D., Vaughan, D. G., and Xie, S.-P.: Technical Summary, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 33–115, 2013.

Thorne, P. W., Donat, M. G., Dunn, R. J. H., Williams, C. N., Alexander, L. V., Caesar, J., Durre, I., Harris, I., Hausfather, Z., Jones, P. D., Menne, M. J., Rohde, R., Vose, R. S., Davy, R., Klein-Tank, A. M. G., Lawrimore, J. H., Peterson, T. C., and Rennie, J. J.: Reassessing changes in diurnal temperature range: Intercomparison and evaluation of existing global data set estimates, Journal of Geophysical Research: Atmospheres, 121, 5138-5158, doi:10.1002/2015JD024584, 2016.

Vincent, L. A., Zhang, X., Brown, R. D., Feng, Y., Mekis, E., Milewska, E. J., Wan, H., and Wang, X. L.: Observed Trends in Canada's Climate and Influence of Low-Frequency Variability Modes, Journal of Climate, 28, 4545-4560, 10.1175/jcli-d-14-00697.1, 2015.

Volosciuk, C., Maraun, D., Vrac, M., and Widmann, M.: A combined statistical bias correction and stochastic downscaling method for precipitation, Hydrol. Earth Syst. Sci., 21, 1693-1719, 10.5194/hess-21-1693-2017, 2017.

Wang, X., Huang, G., Liu, J., Li, Z., and Zhao, S.: Ensemble Projections of Regional Climatic Changes over Ontario, Canada, Journal of Climate, 28, 7327-7346, 10.1175/jcli-d-15-0185.1, 2015.

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., and Viterbo, P.: The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data, Water Resources Research, 50, 7505-7514, doi:10.1002/2014WR015638, 2014.

Wilby, R. L., and Dessai, S.: Robust adaptation to climate change, Weather, 65, 180-185, 10.1002/wea.543, 2010.

https://doi.org/10.5194/hess-2019-249
Preprint. Discussion started: 16 July 2019

Wilby, R. L.: Climate Change in Practice: Topics for Discussion with Group Exercises, Cambridge University Press, Cambridge, 2017.

Willkofer, F., Schmid, F.-J., Komischke, H., Korck, J., Braun, M., and Ludwig, R.: The impact of bias correcting regional climate model results on hydrological indicators for Bavarian catchments, Journal of Hydrology: Regional Studies, 19, 25-41, https://doi.org/10.1016/j.ejrh.2018.06.010, 2018.

Wong, J. S., Razavi, S., Bonsal, B. R., Wheater, H. S., and Asong, Z. E.: Inter-comparison of daily precipitation products for large-scale hydro-climatic applications over Canada, Hydrol. Earth Syst. Sci., 21, 2163-2185, 10.5194/hess-21-2163-2017, 2017.

Woo, M.-k., Lewkowicz, A. G., and Rouse, W. R.: Response of the Canadian permafrost environment to climatic change, Physical geography, 13, 287-317, 1992.

Woo, M.-K., and Pomeroy, J.: Snow and Runoff: Processes, Sensitivity and Vulnerability, in: Changing Cold Environments, John Wiley & Sons, Ltd, 105-125, 2011.

Wood, A. W., Leung, L. R., Sridhar, V., and Lettenmaier, D.: Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs, Climatic change, 62, 189-216, 2004.

Yeh, K.-S., Côté, J., Gravel, S., Méthot, A., Patoine, A., Roch, M., and Staniforth, A.: The CMC–MRB Global Environmental Multiscale (GEM) Model. Part III: Nonhydrostatic Formulation, Monthly Weather Review, 130, 339-356, 10.1175/1520-0493(2002)130<0339:tcmgem>2.0.co;2, 2002.

You, Q., Wang, D., Jiang, Z., and Kang, S.: Diurnal temperature range in CMIP5 models and observations on the Tibetan Plateau, Quarterly Journal of the Royal Meteorological Society, 143, 1978-1989, doi:10.1002/qj.3057, 2017.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B., and Zwiers, F. W.: Indices for monitoring changes in extremes based on daily temperature and precipitation data, Wiley Interdisciplinary Reviews: Climate Change, 2, 851-870, doi:10.1002/wcc.147, 2011.