Climate indices to characterize climatic changes across southern Canada

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Abstract
The present study analyses the impacts of past and future climate change on extreme weather events for southern parts of Canada from 1981 to 2100. A set of precipitation and temperature-based indices were computed using the downscaled Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble projections at 8 km resolution over the 21st Century for two representative concentration pathway (RCP) scenarios: RCP4.5 and RCP8.5. The results show that this region is expected to experience stronger warming and a higher increase in precipitation extremes in future. Generally, projected changes in minimum temperature will be greater than changes in maximum temperature, as shown by respective indices. A decrease in frost days and an increase in warm nights will be expected. By 2100 there will be no cool nights and cool days. Daily minimum and maximum temperatures will increase by 12 and 7°C, respectively, under the RCP8.5 scenario, when compared with the reference period 1981–2000. The highest warming in minimum temperature and decrease in cool nights and days will occur in Ontario and Quebec provinces close to the Great Lakes and Hudson Bay. The highest warming in maximum temperature will occur in the southern parts of Alberta and Saskatchewan. Annual total precipitation is expected to increase by about 16% and the occurrence of heavy precipitation events by five days. The highest increase in annual total precipitation will occur in the northern parts of Ontario and Quebec and in western British Columbia.

KEYWORDS
climate change, climate indices, CMIP5, extreme events, future climate projection

1 | INTRODUCTION
Weather and climate extremes such as heat waves, heavy rain, and snow events and droughts have serious physical and economic impacts on communities. They play an important role in shaping the natural environment (Kunkel et al., 1999; Easterling et al., 2000; McMichael et al., 2006). Therefore, regional and local information on extreme weather events and their predictions is very valuable to stakeholders and policy-makers. Based on the analysis of past observations, the Intergovernmental Panel on Climate Change (IPCC) (2012) showed significant...
changes in extreme weather events. To describe the state and changes in the Earth’s climate system, the Expert Team on Climate Change Detection and Indices (ETCCDI) defined 27 climate indices: 16 for temperature and 11 for precipitation (e.g. Peterson and Manton, 2008; Zhang et al., 2011). These indices describe the past and future changes in the intensity, frequency and duration of extreme temperature and precipitation events. They provide a means to modellers, analysts and policy-makers to understand better the changes in climate and extreme weather events. They can help to quantify the expected implications of extreme events for a region or certain economic sectors (Della-Marta et al., 2009). They are widely used across several disciplines and become an important impact parameter in climate change studies (Christenson et al., 2006; Fischer et al., 2013; Sillmann et al., 2013a, 2013b; Zubler et al., 2014; Wazneh et al., 2017).

Historical and projected changes in temperature and precipitation indices have been analysed in many studies on global and regional scales using the fifth phase of Coupled Model Inter-comparison Project (CMIP5) multi-model ensemble data sets (e.g. Yun et al., 2012; Kharin et al., 2013; Sillmann et al., 2013a; Fischer and Knutti, 2014; Zhou et al., 2014; Jeong et al., 2016). According to the Fifth Assessment Report (AR5) of the IPCC, since the 1950s cool temperature extremes have decreased and warm temperature extremes have increased in the majority of land areas across the globe (Hartmann et al., 2013). Specifically, the numbers of cool days and cool nights have decreased and the numbers of warm days and warm nights have increased, while the intensity of both maximum and minimum temperature extremes have increased, as shown by the analysis of temperature-related indices (Ballester et al., 2009; Simolo et al., 2011; Donat and Alexander, 2012; Hansen et al., 2012).

A significant increase in heavy and very heavy precipitation has been projected across the globe (Flato et al., 2013). Overall, projected increases in extreme precipitation are expected to increase at a faster rate than those in total wet-day precipitation. Hartmann et al. (2013) showed an increase in monthly maximum one day precipitation and extremely wet days over North America. Sillmann et al. (2013a) found that projected decreases in heavy precipitation coincide with increases in consecutive dry days in South Africa, Central America, Australia and the Mediterranean, indicating future intensification of dry conditions. Changes and variability in temperature and precipitation, as shown by climate indices, were most pronounced under representative concentration pathway (RCP) scenario RCP8.5 than RCP4.5 (Hartmann et al., 2013; Sillmann et al., 2013a).

Historical trends in temperature and precipitation in Canada have been investigated in many studies (Zhang et al., 2000, 2011; Vincent and Mekis, 2006; Vincent et al., 2012, 2015). Zhang et al. (2000) found that although the trends differed from region to region, the annual mean temperature in Canada has experienced an increase of approximately 1°C during the latter half of the 20th Century. Zhang et al. (2010) and Vincent and Mekis (2006) showed that the frequency of precipitation events has increased significantly over the 20th Century, even though there has been no identifiable trend in precipitation extremes. A few studies have also evaluated projections of future extreme climate events for Canada (e.g. Mladjic et al., 2011; Mailhot et al., 2012; Asong et al., 2016; Erler and Peltier, 2016; Jeong et al., 2016). Jeong et al. (2016) used data from 11 regional climate models (RCMs) to study the impact of future climate changes on hot days and heat waves across Canada. They found increase in the number of hot days and hot spells; however, there was large spatial variability in the occurrence of these events. Using downscaled data from 120 sites across the Canadian Prairie provinces, Asong et al. (2016) showed that mean precipitation is projected to increase, while minimum and maximum temperatures are also projected to increase. Based on data from four RCMs, Erler and Peltier (2016) showed considerable changes in extreme precipitation across western Canada under the RCP8.5. They found that at the end of the 21st Century, the highest projected precipitation increase is about 30%.

The above studies in the literature that show projected changes in extreme climate indices for Canada have used regional and global climate model (GCM) data sets at large spatial resolutions, with model grid sizes ranging from 40 to 140 km. However, these studies do not cover the entire southern part of Canada, and the indices used cannot show the future extreme climate variation in terms of intensity, frequency and duration.

The goal of the present study is to analyse and quantify climatic changes in southern Canada at high spatial resolution to understand better the trends and impacts of climate change and extreme events. For this purpose, downscaled high-resolution (8 km²) multi-model CMIP5 data produced by the US Department of the Interior’s Reclamation Bureau for two different IPCC emission scenarios (RCP4.5 and RCP8.5) (Taylor et al., 2012) were used to compute temporal and spatial projected changes in temperature and precipitation indices. These data were downscaled using a bias-corrected and constructed analogues (BCCA) method (Reclamation, 2013). The selected climate indices can show variation in terms of intensity, frequency and duration. Canada’s geographical location in the high latitudes makes it one of the few countries that are likely to experience large changes in climate in future. The analysis of future climate trends and extreme events at high spatial resolution has not been conducted in the past across the Canadian landscape, which has large heterogeneity in land surface and diverse climates.
2 | MATERIALS

2.1 | Study region and climate models

2.1.1 | Study region

The present study was conducted in southern Canada, in areas located between 42° 06′ N, 67° 06′ W and 53° 31′ N, 124° 68′ W (Figure 1). This region contains the majority of Canada’s population. As defined by Plummer et al. (2006), it contains seven climatic regions, including Pacific coastal (PC), Pacific mountainous (BCM), Prairie land (PR), and Northwestern and Northeastern forests (NWF and NEF), Great Lakes (GL) and Atlantic region of Canada (AC) (Figure 1). Data from 18,785 grids with 0.125° or 8 km spatial resolution were used in the present study (Figure 1). The distribution of grids in the provinces and climatic region is given in Table 1. New Brunswick (NB) contained the lowest number of data grids used (157, or 0.84% of total grids), while Ontario

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**FIGURE 1** (upper) Study location and climate regions in southern Canada. Red points represent the centroid of bias-corrected and constructed analogues (BCCA) grids (18,785 grids of 0.125° resolution) in the study area; and (lower) climate regions map. Source: Environment Canada (EC), Atmospheric Environment Service, Climate Research Branch, 1998, Climate trends and Variations bulletin for Canada, Ottawa.
(ON) had in the highest number of data grids (6,017, or 32.03%). In terms of climatic region, 56% (10,500 grids) were located in the NEF region and just 2% (352 grids) in the PC region.

### 2.1.2 Climate models

Historical and future climate simulations of the 20th and 21st Centuries produced by the IPCC AR5 participating models and analysed through the CMIP5 initiative were used in the present study (Taylor et al., 2012). The analysis focused on moderate (RCP4.5) and high forcing (RCP8.5) emission scenarios. Data were used from models that provided daily means. Therefore, data from 12 CMIP5 GCMs was used (Table 2). The ensemble models are used to minimize the biases associated with the choice of the individual GCM model and/or a specific greenhouse gas emission scenario. By considering different GCMs and emission scenarios' variability, the ensemble models provide a robust analysis of future climate trends (Tebaldi and Knutti, 2007). The downscaling techniques used in climatological studies are generally regrouped into two main categories: dynamic and statistical. Dynamic downscaling uses high-resolution RCMs nested within the outputs of coarser models (Roads et al., 2003; Weaver, 2004; Antic et al., 2006). However, statistical downscaling is based on a statistical relation between historical coarse resolutions climate records and historical observed local climates. The two downscaling categories are compared in many studies (Murphy, 1999; Hay and Clark, 2003; Wood et al., 2004). In the present study, the daily climate projections downscaled by the BCCA method for southern Canada were used. These data were obtained from data archives of the US Department of the Interior's Reclamation Bureau (https://gdo-dcp.ucolnl.org/downscaled_cmip_projections/dcpInterface.html). A constructed analogue method used for the present data was a statistical downscaling approach based on the idea that if the present weather has an exact analogue in the

### Table 1

Distribution of data grids used in the present study across Canada

| Province               | Number of grids | %    |
|------------------------|-----------------|------|
| British Columbia (BC)  | 2,186           | 11.64|
| Quebec (QC)            | 5,257           | 27.99|
| Saskatchewan (SK)      | 2,102           | 11.19|
| Manitoba (MB)         | 1,586           | 8.44 |
| Ontario (ON)           | 6,017           | 32.03|
| New Brunswick (NB)     | 157             | 0.84 |
| Alberta (AB)           | 1,472           | 7.84 |
| Northeastern forests (NEF) | 10,500      | 56   |
| Atlantic region of Canada (AC) | 495 | 2.5  |
| Great Lakes (GL)       | 818             | 4.5  |
| Northwestern forests (NWF) | 1,042       | 5.5  |
| Prairie land (PR)      | 3,498           | 18.5 |
| Pacific coastal (PC)   | 352             | 2.0  |
| Pacific mountainous (BCM) | 2080        | 11.0 |

### Table 2

Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models (GCMs) used in the present study

| Model         | Institution                                                                 |
|---------------|------------------------------------------------------------------------------|
| ACCESS1       | Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia |
| BCC-CSM1      | Beijing Climate Center, China Meteorological Administration                  |
| CanESM2       | Canadian Centre for Climate Modelling and Analysis                            |
| CCSM4         | National Center for Atmospheric Research (NCAR)                              |
| CESM1-BGC     | Community Earth System Model Contributors                                   |
| CNRM-CM5      | Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique |
| CSIRO-MK3-6-0 | Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence |
| GFDL-ESM2G    | NOAA Geophysical Fluid Dynamics Laboratory                                   |
| Inmcm4        | Institute for Numerical Mathematics                                          |
| IPSL-CM5A-LR  | Institut Pierre-Simon Laplace                                                 |
| MICROC5       | Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology |
| MPI-ESM-LR    | Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)  |
historical record, the future weather should be the analogue of the present data. The length of future prediction in the analogue approach (i.e. time window) depends on the degree of correspondence across all climate variables between historical and present data. For a further description of the BCCA method, see Reclamation (2013).

2.2 Climate indices

For many years, researchers have focused on the mean climatic variations to study the effect of climate change. However, if the distribution of the climate variable does not shift with the mean variation, then the variation would not necessarily lead to a rise in extreme events. Therefore, the ETCCDI defined a set of climate indices to analyse climate variations focusing on the extremes. These indices contain independent information and can be applied to local and regional scales to measure spatial and temporal variability. For detailed information on these indices, see Alexander et al. (2006), Zhang et al. (2011) and Sillmann et al. (2013b). The indices chosen for the present study are similar to those used by Sillmann et al. (2013b). They cover many aspects of a changing climate and give a comprehensive overview of the projected changes in temperature and precipitation extremes across models and scenarios. They can be regrouped into three principal categories: (1) absolute and threshold; (2) duration; and (3) percentile.

In total, 12 indices (eight for temperature and four for precipitation) are used in the present study. Temperature indices include annual minimum of daily minimum temperature (TNn), annual maximum of daily maximum temperature (TXx), frost days (FD), tropical nights (TR), cool nights (TN10p), cool days (TX10p), warm nights (TN90p) and warm days (TX90p). Precipitation indices include annual total precipitation (PRCPTOT), consecutive dry days (CDD), simple daily intensity index (SDII) and heavy precipitation days index (R10). Further details of these indices and their distribution into the three principal categories are presented in Table 3.

The selected climate indices and their anomalies (or exceedance rate for percentile indices) from a predefined reference period were computed and their spatial and temporal evolution for each emission scenario analysed. The used data set covers the period from January 1950 to December 2100; the data from 1950 to 2005 are historical under the historical emissions scenario, while those from 2006 to 2100 are future data under future RCP scenarios RCP4.5 and RCP8.5. These RCPs are used to show the full possible future range of variability for extreme climate indices. In fact, the RCP4.5

### Table 3: Temperatures and precipitation indices used in the present study

| Category               | Indicator                   | ID  | Indicator definition                                      | Units year⁻¹ |
|------------------------|-----------------------------|-----|----------------------------------------------------------|--------------|
| Absolute and threshold | Minimum $T_{\text{min}}$    | TNn | Annual minimum of daily minimum temperature $(T_{\text{min}})$ | °C           |
|                        | Maximum $T_{\text{max}}$    | TXx | Annual maximum of daily maximum temperature $(T_{\text{max}})$ | °C           |
|                        | Frost days                  | FD  | Days with $T_{\text{min}} < 0^\circ$C                    | Days         |
|                        | Tropical night              | TR  | Days with $T_{\text{min}} > 20^\circ$C                    | Days         |
|                        | Heavy precipitation         | R10 | Days when precipitation > 10 mm                           | Days         |
| Duration               | Consecutive dry days        | CDD | Maximum number of consecutive days with total precipitation < 1 mm | Days         |
| Percentile             | Cool nights                 | TN10p| Total number of days when $T_{\text{min}} < 10$th percentile | Days         |
|                        | Cool days                   | TX10p| Total number of days when $T_{\text{max}} < 10$th percentile | Days         |
|                        | Warm nights                 | TN90p| Total number of days when $T_{\text{min}} > 90$th percentile | Days         |
|                        | Warm days                   | TX90p| Percentage of days when $T_{\text{max}} > 90$th percentile | Days         |
| Not classified          | Annual total precipitation  | PRCPTOT| Annual total precipitation from days ≥ 1 mm | mm           |
|                        | Simple daily intensity      | SDII| Sum of precipitation in wet days during the year divided by wet days in the year | mm           |
is a stabilization scenario where total radiative forcing is stabilized around 2050 and the RCP8.5 represents scenarios in the literature leading to high greenhouse gas concentration levels. A set of box-plot diagrams were produced to summarize regional and provincial features of the projected changes. The following first presents the temperature indices projected changes, then those of precipitation indices.

### 3.1 Temperature indices

#### 3.1.1 Temporal variability

Global averages of temperature indices across all 18,785 grids computed for the period 1950–2100 for the RCP4.5 and RCP8.5 are presented in Figure 2. The ensemble median is indicated by the solid lines and the

**FIGURE 2** Averages of temperature indices over southern Canada as simulated by the Coupled Model Intercomparison Project Phase 5 (CMIP5) for representative concentration pathway (RCP) scenarios RCP4.5 (red) and RCP8.5 (green). The median is indicated by the solid lines; the interquartile (25th and 75th quantiles) ensemble is indicated by the shaded lines. Change are displayed as (a) anomalies from the reference period 1981–2000 for absolute and threshold indices; and (b) exceedance rate of change (%) from the reference period 1961–1990 for percentile indices.
interquartile by the shaded lines. Shown are the anomalies from the reference period 1981–2000 for absolute and threshold indices (Figure 2a) and the exceedance rate (%) from the reference period 1961–1990 for percentile indices (Figure 2b). Note that percentile-based indices are sensitive to the selected reference period compares with absolute and threshold indices (Sillmann et al., 2013a). Therefore, based on several sensitivity tests, Sillmann et al. (2013b) suggest using 1961–1990 as a reference period for percentile indices since 1981–2000 is an abnormally warmer period. Relative to the reference period, an increase in minimum temperature (TNn) and maximum temperature (TXx) was observed over southern Canada in the 21st Century (Figure 2a). For different RCPs, the increase of TNn was greater than that in TXx. In terms of multi-model ensemble median, by the end of the 21st Century and for RCP8.5: (1) the TNn and TXx increased by 12.4 and 7°C, respectively; (2) the FD decreased by about 55 days; and (3) the TR increased by about 14 days. The lower part of Figure 2 shows a

**FIGURE 3** Projected changes of temperature indices temporally averaged over the period 2081–2100 for representative concentration pathway (RCP) scenarios RCP4.5 (red) and RCP8.5 (green). Change are displayed as (a) anomalies from the reference period 1981–2000 for absolute and threshold indices; and (b) exceedance rate of change (%) from the reference period 1961–1990 for percentile indices. Each box shows the median and quartiles of indices over the studied region for a specified Coupled Model Intercomparison Project Phase 5 (CMIP5) model. Changes are shown for all 12 models used in this analysis.
consistent decrease in cool nights and days, and an increase in warm nights and days over southern Canada in the 21st Century (Figure 2b). In terms of multi-model ensemble median, by the end of the 21st Century and for the RCP8.5: (1) the TN10p and TX10p decreased from 12% to 0%; and (2) the TN90p and TX90p increased from 10% to about 51 and 48%, respectively. The changes in cool and warm days appear to be somewhat smaller compared with the cool and warm night frequency changes. A low variation in temperature indices was observed between the middle and end of the 21st Century under the RCP4.5 (+2°C for the TNn, +0.8°C for the TXx, −10 days for the FD, +1 day for the TR, −1% for the TN10p, −0.5% for the TX10P, +5% for the TN90p and +4% for the TX90p) compared with those under the RCP8.5 (+7.5°C for the TNn, +3.4°C for the TXx, −30 days for the FD, +12 days for the TR, −3% for the TN10p, −2.5% for the TX10P, +20% for the TN90p and +18% for the TX90p).

Projected changes of temperature indices across southern Canada for all 12 models used in this analysis, and temporally averaged over the period 2081–2100, for the RCP4.5 and RCP8.5 are presented in Figure 3. Box-plot whiskers display the full range of variation across southern Canada; the horizontal line indicates the median variation. The warmest future change is obtained using ACCES1 and MICRO5 models. In fact, these models simulate the highest increase in minimum and maximum temperatures, highest decrease in frost days, highest increase of tropical nights, fewer cool nights and days, and more warm nights and days, compared with the other CMIP5 models. Therefore, the coldest future changes are obtained using GFDL-ESM2G and Inmcm4 models (i.e. these two models simulate the lowest increase in minimum and maximum temperatures, lowest decrease in frost days, lowest increase of tropical night, more cool nights and days, and less warm nights and days compared with the other CMIP5 models). It was found that variability across the studied region of indices based on minimum temperature (i.e. TNn) is larger than that based on maximum temperature (TXx) (Figure 3a). Also, the variability in cool nights and days depends on the CMIP5 model used, which is not the case of warm nights and days (same variability using all the CMIP5 models).

FIGURE 4  Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble median of temporally averaged changes in the absolute and threshold temperature indices over the period 2081–2100 displayed as anomalies from the reference period 1981–2000 for representative concentration pathway (RCP) scenarios RCP4.5 (right) and RCP8.5 (left) scenario
models) (Figure 3b). This means that temperature distributions simulated for this region using the CMIP5 models have a different lower tail and a close upper tail.

### 3.1.2 Spatial variability

The spatial variability of the projected change of absolute and threshold temperature indices, displayed as anomalies over the reference period 1981–2000 using the CMIP5 multi-model median, and temporally averaged over the period 2081–2100, for the RCP8.5 and RCP4.5, is shown in Figure 4. For the RCP8.5, the projected changes of absolute and threshold temperature indices across southern Canada are: (1) between 2 and 14°C for the TNn; (2) between 1.5 and 8.5°C for the TXx; (3) between −15 and −55 days for the FD; and (d) between 0 and 50 days for the TR. The highest warming in the TNn occurs in ON and Quebec (QC) provinces close to the GL and Hudson Bay. The lowest warming is in the British Columbia (BC) mountains part. The highest TXx warming occurs in the south of Alberta (AB) and Saskatchewan (SK). Therefore, the lowest warming occurs in the north of QC. For the FD, the highest projected changes are in the northwest of QC, the northeast of ON, and the west of AB and BC. The highest TR occurs in southern ON close to the GL region. Figure 5 shows the spatial variability of projected change in the threshold temperature indices. The highest decrease in cool nights and days occurs in the eastern part of southern Canada, and especially in the northern part of QC and ON close to Hudson Bay. The highest increase in warm nights and days occurs, respectively, in the western and northern parts of southern Canada. More precisely, the highest increase in warm
nights occurred in BC (mountain region), and the increase of warm days in ON close to the GL.

The projected changes of temperature indices, temporarily averaged over the period 2081–2100 and using the CMIP5 multi-model ensemble median in the seven climate regions (defined in Figure 1) are presented in Figure 6. Generally, the projected change varies with respect to the climate regions. Therefore, the two climatic regions NWF and PR have a close median and variability range for the eight indices, which means they are homogeneous in terms of temperature indices. The strongest warming in minimum temperature and highest decrease in cool night and cool days occurs in the NEF, AC and GL climate regions. The two regions PC and BCM have the strongest decrease of frost days and the highest increase in warm nights and warm days. The highest increase (with large variability) for tropical nights is modified in the GL region. Therefore, the highest decrease (with large variability) for frost days occurs in the PC region.

FIGURE 6 Projected changes of temperature indices temporarily averaged over the period 2081–2100 for representative concentration pathway (RCP) scenarios RCP4.5 (red) and RCP8.5 (green). Change are displayed as (a) anomalies from the reference period 1981–2000 for absolute and threshold indices; and (b) exceedance rate of change (%) from the reference period 1961–1990 for percentile indices. Each box shows the median and quartiles of indices using the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble median for a specified climate region. Changes are shown for all seven climate regions used in the study.
Figure 7 shows the projected changes for the different provinces of temperature indices, temporally averaged over the period 2081–2100 for representative concentration pathway (RCP) scenarios RCP4.5 (red) and RCP8.5 (green). Change are displayed as (a) anomalies from the reference period 1981–2000 for absolute and threshold indices; and (b) exceedance rate of change (%) from the reference period 1961–1990 for percentile indices. Each box shows the median and quartiles of indices using the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble median for a specified province. Changes are shown for seven provinces of Canada.

Figure 7 shows the projected changes for the different provinces of temperature indices, temporally averaged over the period 2081–2100, and using the CMIP5 multi-model ensemble median. Box-plot whiskers display the full range of variation across the provinces; and the horizontal line indicates the median variation. The projected change varies with respect the province. QC and ON have the highest warming in minimum temperature and decrease in cool nights and cool days (for the RCP8.5: +12.3°C for the TNn, about −10% for cool nights and days). BC and AB have the lowest warming in minimum temperature and the lowest decrease in cool night and days and the strongest decrease of frost days (for the RCP8.5: +8.5°C for the TNn, about −9% for cool nights and days, between −55 and −70 days for the FD). For maximum temperature (i.e. TXx), the three provinces SK, Manitoba (MB) and AB have the highest warming (about 7°C for the RCP8.5) and the two provinces QC and NB have the lowest warming (about 5.7°C for the RCP8.5). The highest increase in the TR is occurs in MB with an
increase of about 20 days under the RCP8.5. The three provinces BC, SK and AB have non-projected changes in the TR for the period 2081–2100 under the RCP4.5. In terms of variability, it is argued that the higher variability in (1) the TNn are found in BC, QC and ON; (2) the TXx was found in all provinces; (3) the FD was found in BC, ON and AB; (4) the TR was found in QC, SK, MB and ON; (5) the TN10p was found in BC, SK and AB; (6) the TX10p was found in BC, ON and AB; (7) the TN90p was found in BC; and (8) the TX90p was found in BC and ON.

3.2 Precipitation indices

3.2.1 Temporal variability

Global averages for changes in precipitation indices displayed as relative change to the 1981–2000 reference period, across the studied region and simulated by the CMIP5 ensemble median, are shown in Figure 8. Precipitation indices time series were smoothed with a 10 year running mean filter. Relative to the reference period, an increase in PRCPTOT, SDII and R10 is observed, as well as a decrease in the CDD indices. More precisely, for RCP8.5, the PRCPTOT and SDII were projected to increase by 17% and 11%, respectively, by the end of the 21st Century, whereas the R10 is projected to increase by five days. For the CDD, it is expected to decrease by one day by the end of 2100. A significant variation for precipitation indices was found between the middle and end of the 21st Century (for the RCP4.5, the PRCPTOT increases from 6% to 11%, the SDII increases from 3% to 7%, and the R10 increases from 1% to 3%). Generally, the change under the RCP8.5 is higher than under the RCP4.5.

The projected changes in precipitation indices across Canada averaged over the period 2081–2100 and computed for different CMIP5 models are presented in Figure 9. The wettest model in terms of average across the whole grids is the GFDL-ESM2G. In fact, for the RCP8.5, the global averages of projected changes in the period 2081–2100 using the GFDL-ESM2G model are +26% for the PRCPTOT, 15% for the SDII, +7 days for the R10 and −3.5 days for the CDD. The dryer model is

**FIGURE 8** Averages of percentile precipitation indices over southern Canada as simulated by the Coupled Model Intercomparison Project Phase 5 (CMIP5) for representative concentration pathway (RCP) scenarios RCP4.5 (red) and RCP8.5 (green) displayed as relative change. Precipitation indices time series are smoothed with a 10 year running mean filter. The median is indicated by the solid lines and interquartile (25th and 75th quantiles) ensemble is indicated by the shaded lines.
the CSSM4 with a 2% change for the PRCPTOT, a 4% change for the SDII and a 1.5 days change for the R10. A non-intermodel agreement on the variation of the CDD was found (i.e. the sign of the projected CDD depends on the model choice). In fact, the global average of the projected changes in the CDD across the studied region is positive using the inmcm4 and IPSLCM5ALR, and negative using the other CMIP5 models list.

### 3.2.2 Spatial variability

The spatial variability of the projected change of precipitation indices using the CMIP5 multi-model median, temporally averaged over the period 2081–2100, and for the RCP8.5 and RCP4.5, is shown in Figure 10. For the RCP8.5, the projected changes of the precipitation indices across Canada are: (1) between 0% and 25% for the PRCPTOT; (2) between 0% and 20% for the SDII; (3) between −5 and 7.5 days for the CDD; and (4) between 0 and 10 days for the R10. The lowest PRCPTOT and SDII increase occurs in the centre of the studied region in MB close to the lakes of Winnipeg and MB. The highest increase in the PRCPTOT and SDII occurs in the northern parts of QC and ON and in western BC (mountain region). For the CDD indices, generally a decreasing projection is shown in the most part southern Canada. Therefore, an increasing projection of the CDD (i.e. more dry days) is shown in the south of BC and in ON close to Lake Ontario. The higher R10 projection is shown in the northeast of QC (a rural region with a high number of lakes).

Relative projected changes of precipitation indices averaged over 2081–2100 and using the CMIP5 multi-model ensemble median for the seven climatic regions are presented in Figure 11a. It can be observed that, generally, the projected change in the precipitation indices varies with respect to the climatic region. For the PRCPTOT and R10 indices, the higher increase relative to the reference period was in the NEF region (18% and 6 days for the RCP8.5, respectively); and the lower increase was in the PR and NWF regions (12% and 2 days for the RCP8.5, respectively). For the SDII indices, the higher relative changes occurs in PC and BCM (14% for the RCP8.5); therefore, the lower increase occurs in the NWF and PR regions (8% for the RCP8.5). The sign of changes for the CDD indices varies between the climatic regions. In fact, the CDD is projected to increase in the PC and BCM climatic regions and to decrease elsewhere in the studied region. The highest decrease of the CDD occurs in the NWF region (−2 days for the RCP8.5) and the highest increase occurs in the PC region (+4 days). For the PRCPTOT and SDII indices, a higher variability is expected in the NWF, PR and BCM regions. The CDD and R10 have a higher variability in NEF, PC and BCM.

In terms of provinces, QC and ON are projected to experience the highest increase in the PRCPTOT (about 17% for the RCP8.5) (Figure 11b). Therefore, the lowest projected increase occurs in BC and AB (11% for the RCP8.5). For the SDII, the highest increase is in BC.
(about 14%) for the RCP8.5), which can be explained by the increase in the CDD in this province. The strongest projected relative change for the R10 occurs in QC (6 days for the RCP8.5), and the lowest changes occur in SK (2 days for RCP8.5). The authors also observed a high variability in the projected changes of the precipitation indices in BC and AB. In addition, a higher R10 variability in QC and ON was observed.

4 | DISCUSSION

In the present study, spatial and temporal projected changes in temperature and precipitation indices defined by the Expert Team of Climate Change Detection and Indices (ETCCDI) are analysed over southern areas of Canada. These climate indices were computed using the daily climate CMIP5 multi-model projections of the 21st Century for two RCP scenarios, regridded and downscaled by the BCCA method at a 0.125° resolution. The results generally indicate an intensification with increasing radiative forcing in the temperature and precipitation indices. The results obtained are consistent with previous studies reported in the literature using observation and climate models (e.g. Frich et al., 2002; Kiktev et al., 2003; Min et al., 2011; Sillmann et al., 2013a, 2013b). However, the results are not directly comparable with theirs because more localized scales and different regions were used herein. The results give more robust information for planners and policymakers with which to determine the impacts of climate extremes at the local scale on the communities and vulnerable populations. The present paper will also help to develop flooding prevention and adaptation-related policies for communities and provinces across southern Canada.
Many studies have investigated the influence of land–atmosphere coupling on indices of extreme temperature. In the present study, a strong minimum temperature warming is founded in the QC and ON regions and close to the GL. This warming can be associated with several different mechanisms, including reductions in fall/winter ice and snow cover, increased summer ocean heating, as well as changes in surface heat fluxes (e.g. Screen and Simmonds, 2010; Flanner et al., 2011). However, a large increase in maximum temperature is found in AB, SK and MB. These provinces have the lowest projected increase in annual total precipitation. The global analysis of Mueller and Seneviratne (2012) identified a relationship between precipitation deficits and maximum warming across the world, including many areas in North and South America, Europe, Australia, and parts of China. They found that the daily maximum temperature distribution is shifted to higher values on days

![Figure 11](image-url)
following low soil moisture anomalies. Therefore, the stronger increase in maximum temperature in these provinces can be related to soil-moisture feedbacks.

For southern Canada, the asymmetry observed in historical minimum and maximum temperatures (e.g. Vincent and Mekis, 2006; Zhang et al., 2011) continues and intensifies with increasing emissions in the future climate projections. In fact, the warming of indices based on minimum temperature (e.g. T\text{Min}, FD, TR) is larger than in indices based on maximum temperature (e.g. T\text{Max}, TX10p, TX90p). Note that many studies have shown that warming based on minimum temperature is underestimated, and warming based on maximum temperature is overestimated, using the CMIP5 data sets over the latter half of the 20th Century (Zwiers et al., 2011). Therefore, the expected contrast in changes between minimum and maximum temperatures trends are even larger than simulated by the CMIP5.

To quantify the GCM's reliability in terms of estimated observed extreme climate indices, trends from downscaled CMIP5 models must be compared with those from observed data using historical periods (e.g. Wu and Huang, 2016; Xu et al., 2019a, 2019b). The present analysis was recently completed for this region using 48 weather stations located in southern ON (Wazneh et al., 2017). The results generally show that climate indices estimated by Canadian RCMs and GCMs are warmer and wetter than those estimated using observed data. The bias in the estimation of temperature indices is generally smaller than that in precipitation indices (i.e. GCMs reproduce better trends for temperature indices than those of precipitation indices). It was found that the bias-correction method improves the ability of the GCMs to simulate observed trends in climate indices accurately.

Major environmental and economic impacts can be caused by the changes in extreme temperature and precipitation events in Canada. For example, the demand for heating buildings and for energy consumption can be influenced by the number of cool and frost days. The summer recreational season can be extended with more summer days, but winter activities can be reduced. An increase in annual total precipitation can lead to severe flood events in future across the country. Warmer temperatures in some regions can be beneficial for agriculture because they will be accompanied by longer frost-free seasons and better temperatures for agriculture (Vincent and Mekis, 2006). However, excessive warming can increase evaporation, which will likely result in a lowering of water levels in lakes, affecting the seasonal climate dynamic and water quality.

The main limitation of the present study arises from the lack of seasonal analysis of future climate projections for different climate scenarios. Furthermore, additional work will be required to assess the relation between the projected changes in temperature and precipitation extremes and changes in regional atmospheric circulation patterns (e.g. the Arctic and North Atlantic Oscillations) and other mechanisms such as soil moisture, snow and vegetation for southern Canada. Characterizing and separating the impact of each of these factors will be a very difficult task and beyond the scope of the present study; however, it will be crucial for a comprehensive understanding of the future changes simulated for this region.

The GCMs and RCMs do not necessarily respond in the same way to a given future forcing scenario. These differences are due to scientific uncertainties about how the climate system works, differences in the way various subsystems are modelled (e.g. land-surface processes), and differences in how unresolved processes are parameterized (e.g. convection) (Raisanen, 2007). These uncertainties can be explored and characterized by analysing the results of different climate models that are subjected to the same future radiative forcing. In the present study, uncertainty analysis (Figures 3 and 9) shows a large difference among the 11 GCMs under the two RCP scenarios, and the uncertainty ranges tend to be larger under a higher emission scenario. For temperature indices (Figure 3), the long-term projected difference under various emission scenarios tends to be larger than those by different climate models and, hence, can be the dominant contributor to the projection uncertainty of those indices. Note that a solution to ensure the accuracy of projected climate indices is to use the ensemble GCMs (as is the case in the present study) rather than select one of the GCMs (e.g. Wu and Huang, 2016). In addition, note that some other uncertainty sources, such as bias-correction methods (Fowler et al., 2007), spatial resolution and internal variability (Zhou et al., 2014), are overlooked in the present study. Future research is, therefore, needed to quantify the relative contributions of these sources to the projection uncertainty of extreme precipitation and temperature indices at regional scales.

In term of models, for southern Canada the warmest projected changes scenario were obtained using the ACCESS1 developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM, Australia), and the coldest projection was obtained using the GFDL-ESM2G developed by the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory. The wettest projected changes were obtained using the GFDL-ESM2G, and the driest changes using the CSSM4 model developed by the National Center for Atmospheric Research (NCAR). It will be interesting in future to evaluate the ability of CMIP5 members to simulate historical observed climate indices for all southern Canada. The
results of such a study can help to compromise the number of GCMs that can be included in future climate change impact studies for this region.

5 CONCLUSIONS

In the present study, the spatial and temporal changes in past and future temperature and precipitation trends across southern Canada are analysed using a range of climate indices, for example, the annual minimum of daily minimum temperature (TNn), annual maximum of daily maximum temperature (TXx), frost days (FD), tropical nights (TR), cool nights (TN10p), cool days (TX10p), warm nights (TN90p), warm days (TX90p), annual total precipitation (PRCPTOT), consecutive dry days (CDD), simple daily intensity index (SDII) and heavy precipitation (PRCPTOT), warm nights (TN90p), warm days (TX90p), annual total precipitation (PRCPTOT), consecutive dry days (CDD), simple daily intensity index (SDII) and heavy precipitation (PRCPTOT), warm nights (TN90p), warm days (TX90p), annual total precipitation (PRCPTOT), consecutive dry days (CDD), simple daily intensity index (SDII) and heavy precipitation (PRCPTOT). Therefore, the lowest projected increase in R10 projection occurred in the northern part of QC and ON and in northeast ON close to the GL region. For precipitation indices, the highest increase in the PRCPTOT and SDII occurred in the northern part of QC and ON and in west BC (mountain region). The higher R10 projection is shown in northeast QC (a rural region with a high number of lakes). In terms of provinces, QC and ON are projected to experience the highest increase in PRCPTOT. Therefore, the lowest projected increase occurs in BC and AB. In general, note the high spatial variability of climate indices across southern Canada.

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