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Original research article

Evaluation of observed and projected extreme climate trends for decision making in Six Nations of the Grand River, Canada

Tariq A. Deen[a,b,*], M. Altaf Arain[a,b], Olivier Champagne[a,b], Patricia Chow-Fraser[b,c], Nidhi Nagabhatla[a,d], Dawn Martin-Hill[e]

[a] School of Earth, Environment & Society, Hamilton, Ontario, Canada
[b] McMaster Centre for Climate Change, McMaster University, Hamilton, Ontario, Canada
[c] Department of Biology, McMaster University, Hamilton, Ontario, Canada
[d] United Nations University Institute on Comparative Regional Integration Studies (UNU-CRIS), Bruges, Belgium
[e] Department of Anthropology, McMaster University, Hamilton, Ontario, Canada

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ABSTRACT

Hydrometeorological events have been the predominant type of natural hazards to affect communities across Canada. While climate change is a concern to all Canadians, Indigenous communities in Canada have been disproportionately more affected by these extreme climate events than non-Indigenous communities. As the impacts of climate change intensify, it becomes increasingly important that high-resolution climate services are made available to Indigenous decision makers for the development of climate change adaptation plans. This paper examined extreme climate trends in the Six Nations of the Grand River reserve, the most populated Indigenous community in Canada. A set of 12 indices were used to evaluate changes in extreme climate events from 1951 to 2013, and 2006 to 2099 under Representative Concentration Pathways (RCP) 4.5 and 8.5. Results indicated that from 1951 to 2013, Six Nations became warmer and wetter with an average temperature increase of 0.7 °C and precipitation increase of 42 mm. Over this period, the frequency and duration of extreme heat and extreme precipitation events also increased, while extreme cold events decreased. In the future (2006 to 2099), temperature is expected to increase by 3 to 6 °C, while seasonal precipitation is expected to increase in winter, early spring, and fall. Projected rate of increase of heatwaves is 0.4 to 1.5 days per year and extreme annual rainfall events is 0.2 to 0.5 mm per year under both RCP scenarios. The climate information and data provide by this study will help Six Nations' decision makers in planning for climate change impacts.

1. Introduction

The Intergovernmental Panel on Climate Change's (IPCC) special report stated that climate change continues to remain the foremost environment crisis facing communities around the world (IPCC, 2018). Despite sustained efforts to mitigate carbon dioxide and other greenhouse gas emissions through international environmental treaties (UN, 1994; UN, 1998; UN, 2015), greenhouse gas levels have continued to increase since the 1980s (Ritchie and Roser, 2020). As a result, global surface temperatures have risen rapidly resulting in multifaceted biophysical impacts around the world (IPCC, 2013; 2014). While it remains challenging to link specific extreme climate events to climate change, it is understood that increases in surface temperatures will influence the pattern, intensity, and duration of extreme events (Kundzewicz 2008). Extreme events cause devastating loss of human life and financial damages for individuals and communities around the world. Public Safety Canada (2016) records indicate that between 1911 and 2016 Ontario experienced 164 hydrometeorological disasters, the majority of which were floods (64) followed by storms (thunder, winter, or unspecified) (41), drought (7), cold events (6), heat events (5), and hurricanes (2). These disasters have resulted in number of deaths and over a billion dollars in financial damages in the province.

Multiple studies have suggested that climate patterns in Ontario will change over the course of this century. Using the Special Report on Emissions Scenarios (SRES) A1B, A2 and B2 Wang et al. (2014; 2015) and Li et al. (2018) found that air temperature will increase in several

* Corresponding author at: Burke Science Building, Room 313, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4K1, Canada.
E-mail addresses: deenta@mcmaster.ca (T.A. Deen), arainm@mcmaster.ca (M.A. Arain), champago@mcmaster.ca (O. Champagne), chowfras@mcmaster.ca (P. Chow-Fraser), nagabhn@mcmaster.ca (N. Nagabhatla), dawnm@mcmaster.ca (D. Martin-Hill).

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Southern Ontario cities over the 21st century. Additionally, Wang et al. (2015) findings suggested that average temperature in Ontario may increase by ~ 2 °C per 30-year interval (2020–2099), while McDermid et al. (2015) found that annual temperature in the Great Lakes region will increase 2.3 to 7.9 °C throughout the 21st century under Representative Concentration Pathways (RCP) 2.6, 4.5, and 8.5. Furthermore Li et al. (2018) results indicated that heat waves will increase along the Toronto-Windsor corridor. With respect to precipitation, McDermid et al. (2015) found that 21st century annual precipitation in the Great Lakes region will increase between 72 and 123 mm under RCP 2.6, 4.5, and 8.5, however summer precipitation may decrease under RCP 4.5 and 8.5. Deng et al. (2016) projected that between 2046 and 2100 average precipitation, and precipitation extremes will increase throughout Southern Ontario, and a study of projected precipitation patterns in the Grand River watershed found that between 2071 and 2100 winter-spring precipitation will increase while summer precipitation will decrease leading to potentially stronger flooding and droughts in these areas (Li et al., 2016). As climate changes and extreme events become more frequent and severe, individuals and communities who have not adapted their systems, infrastructure, or disaster response plans to these changes will experience impacts of a magnitude greater than had previously been planned for.

Despite Indigenous communities being disproportionately affected by climate change and extreme climate events in Canada and globally (IPCC 2014; Public Safety Canada 2019), there has been a lack of studies in the literature that focuses on how climate change is affecting temperature and precipitation patterns, and extreme events' trends in Canadian Indigenous communities. There is an urgent need to create high-resolution climate data products and information that spatially focuses on Indigenous community areas so that it can be used by the decision makers to assess how climate change will affect their community and make plans to deal with these impacts. The use of climate services are an integral component of climate change adaptation planning and extreme climate events preparedness. Moser & Ekstrom (2010) state that climate information is important to nearly every stage of climate change adaptation planning, and that the lack of information and data is a barrier in the planning stage of climate change adaptation. Specifically, the lack of information and data limits the ability of practitioners to assess adaptation options. Additionally, the use of high-resolution climate services has also been highlighted for effective adaptation planning. One of the findings from the Climate Services for Disaster Risk Reduction workshop (2018) found that "[climate services] that draw on high-resolutions exposure and vulnerability information" can help support climate change adaptation planning and disaster risk reduction preparedness (Street et al., 2019, p.30). Furthermore, climate information derived from high-resolution temperature and precipitation extreme projections have been suggested to be useful for determining potential climate change impacts and inform future infrastructure planning (Kotamarthi et al., 2016). Therefore, use of high spatial resolution climate services like the North American CORDEX Program (Mearns et al., 2017) or Ontario Climate Change Data Portal to create locally scaled climate information or datasets are essential for local decision making and planning, and to develop climate resiliency and adaptation plans to reduce community vulnerability to climate change.

Considering these aspects, the objective of this study is to conduct a trend analyses of past (observed) and future (predicted) climatic changes and extreme climate events for the Six Nations of the Grand River reserve area in the Great Lakes region, Canada from 1951 to 2099. Based the joint CCl/WCRP/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) initiative, we calculated in total 12 extreme climate indices using observed temperature and precipitation data from daily gridded meteorological dataset from Natural Resources Canada and simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) framework. This is the first study where ETCCDI indices have been used to analyze the past and projected trends of climatic changes and extreme climate events in an Indigenous community area in Canada. It is anticipated that the climate information and data produced by this study will be used by the community to better understand climate change impacts and extreme climate event trends in the area.

2. Methods

2.1. Study area

The study area is centered on the Six Nations of the Grand River ("Six Nations") reserve (also known as Six Nations Indian Reserve No. 40) in the Great Lakes region in Canada (Fig. 1). Six Nations is a Haudenosaunee community comprised of six nations- Cayuga, Mohawk, Seneca, Onondaga, Oneida, and Tuscarora. It is the largest First Nations community by population in Canada with 27,559 members (12,892 members living on the reserve), and the second largest community by area (~186 km^2) (Six Nations Council, 2019). The study area also covers parts of surrounding community areas, including parts of the City of Hamilton in the northeast, Brant County (part of the City of Brantford) in the west, Norfolk County in the south and Haldimand County (including Caledonia) in the east.

The majority of Six Nations area falls within the McKenzie Creek sub-watershed, with a small northern portion of the community located within the boundary of the Grand River watershed. The McKenzie Creek sub-watershed is an intermediate sized tributary of the Grand River covering a drainage area of 368 km^2. Land cover of the sub-watershed consists of agricultural lands (~70%), forests and wetlands (~25%), and urbanized areas (<5%) (MacVeigh et al., 2016). Additionally, the Six Nations portion of sub-watershed contains the largest block of Carolinian forest (mostly of deciduous broad-leaf trees) in Canada. The climate of the region is humid continental (Dfb/Dfa) with cold winters and hot summers. Winters are milder due to proximity of Lake Erie and Lake Ontario (MacVeigh et al., 2016).

Like many communities in Southern Ontario Six Nations regularly experiences extreme weather events. With respect to hydrometeorological hazards, flooding is of particular concern for the community. Within Six Nations there are three water bodies running through the reserve- the Grand River, the McKenzie Creek, and the Boston Creek (Fig. 1 above). During winter and spring months the Grand River experiences ice jams at the City of Brantford causing areas downstream to become increasingly susceptible to flooding. Intense rainfall can also cause flooding in Six Nations. For example, in January 2020 the area surrounding Six Nations experienced 40 to 80 mm of rainfall within 24 h resulting in Grand River discharge to peak at 950 m^3/s, causing road closures within the community (Thompson, 2020). The McKenzie Creek is also vulnerable to flooding where large precipitation events may inundate low-lying areas of the sub-watershed such as the Ohsweken community area; in 1954 Hurricane Hazel had flooded most of the areas of Six Nations that surrounded the McKenzie Creek. Drought is also a concern for Six Nations. Based on data from the Canadian Drought Monitoring Services (Agriculture and Agri-Food Canada, 2021), between 2002 and 2021 there were 38 months with moderate droughts (defined as events occurring every 5–10 years), 13 months with severe drought (defined as events occurring every 10–20 years), and 4 moths with extreme drought (defined as events occurring every 20–25 years) in or within 10 km of the Six Nations area.

2.2. Data

Daily values of temperature (minimum and maximum) and precipitation data were used to characterize extreme climate events. Due to the relatively low spatial variability of Six Nations an average of the gridded data values was used instead of the values from each individual data grid. The observed data were obtained from the gridded Natural Resources Canada meteorological dataset (NRCANmet) developed by Hopkinson et al. (2011) and McKenney et al. (2011) at ~ 7 × 9 km grids

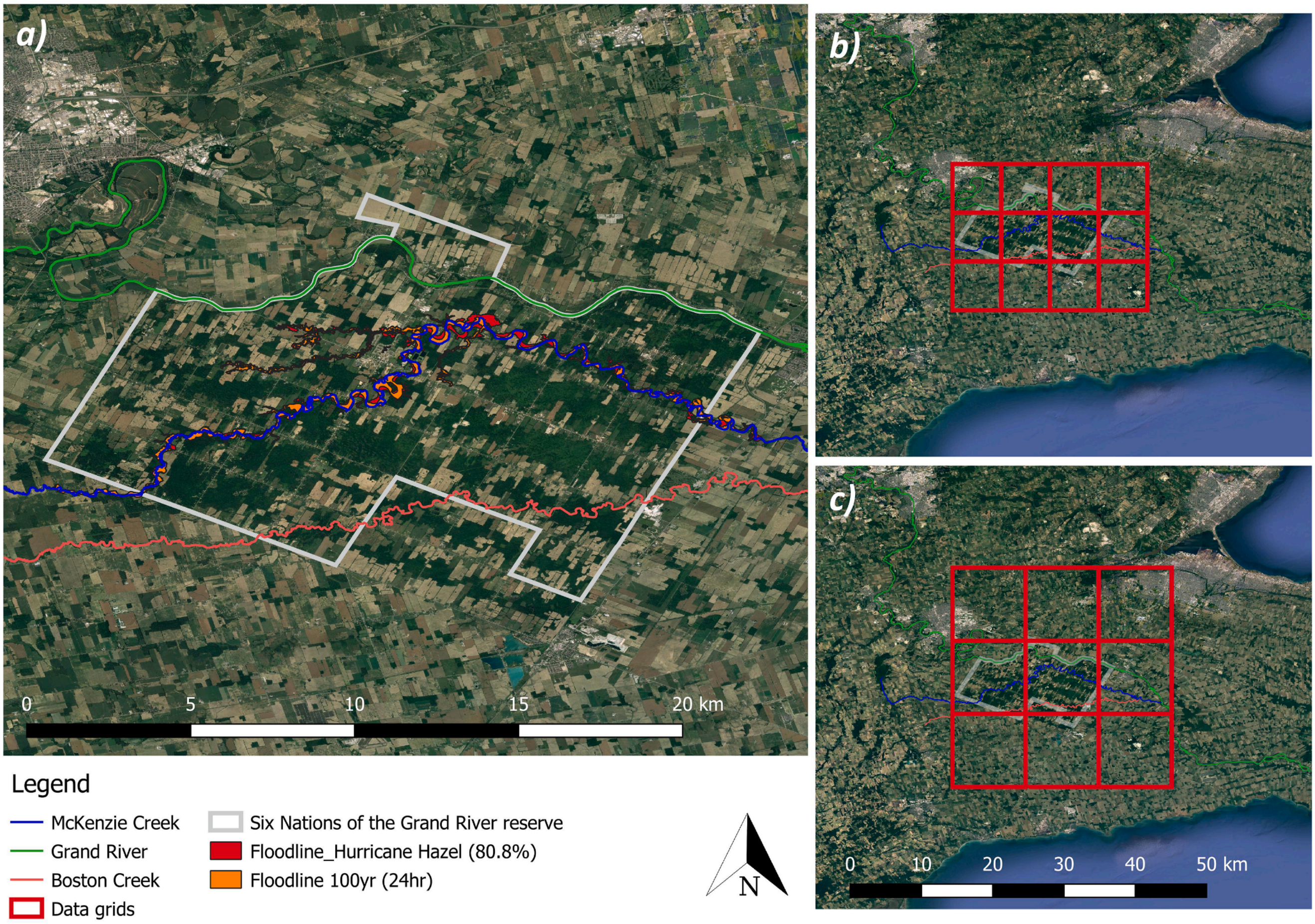

Fig. 1. (a) Map of Six Nations of the Grand River reserve (white outline) with the Grand River (bolded green line), the McKenzie Creek (bolded blue line), and the Boston Creek (bolded pink line). McKenzie Creek flood-lines are overlaid with 100-year flood-line (orange) and Hurricane Hazel flood line (red) (floodline shapefiles that were used were created during the development of the Six Nations of the Grand River Territory: McKenzie Creek Master Drainage and Flood Remediation Plan (Stragis, 2016)). Data grids used in the study are overlaid on top of the Six Nations area in red, (b) observed NRCANmet data grids and (c) simulated CMIP5 data grids.

from 1951 to 2013. The simulated dataset is comprised of 11 Global Climate Models (GCM) from the downscaled Coupled Model Intercomparison Project Phase 5 (CMIP5) climate projections (Table 1) (Taylor et al., 2012). Simulations include a historical period (1951 to 2005) and a projected period (2006 to 2099) and were conducted for two climate change scenarios, Representative Concentration Pathway (RCP) 4.5 and 8.5. RCP 4.5 is an intermediate climate change pathway in which carbon dioxide emissions continue to increase until the mid-21st century after which emissions begin to level out. RCP 8.5 represents a high climate change pathway in which carbon dioxide emissions and population continue to increase throughout the 21st century (van Vuuren et al., 2011). The CMIP5 data from the GCMs were downscaled using the Bias Corrected Spatial Disaggregation (BCSD) method that is a combination of (1) a bias correction technique using the quantile maps technique, and (2) a spatial disaggregation from the GCMs resolution to 1/8° resolution (Brekke et al., 2013). To validate the CMIP5 downscaled data, an average of daily precipitation and temperature values from 1951 to 2005 was taken for each model and compared to observed NRCANmet daily average values from 1951 to 2005. Results indicated a strong correlation between the downscaled and observed data with coefficient of determination (R^2) ranging between 0.72 and 0.91 (0.93 for averaged model ensemble) for precipitation (Fig. 2), and 0.99 for minimum and maximum temperature values (Fig. 3).

Table 1
Global Climate Models used in the study.

Modeling Center	Model Name
Institute Pierre Simon Laplace Model CM5A-LR	IPSLCM5ALR
Russian Institute for Numerical Mathematics Climate Model Version 4	INMCM4
Model for Interdisciplinary Research On Climate version 5	MIROC
National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory Earth System Models	GFDLESM2M GFDLESM2G
Commonwealth Scientific and Industrial Research Organisation	CSIRO
Centre National de Recherches Meteorologiques Coupled Global Climate Model Version Five	CNRMCM5
The fourth version of the Community Climate System Model	CCSM4
Canadian Centre for Climate Modelling and Analysis the Second Generation Earth System Model	CanESM2
Beijing Climate Center Climate System Model	BCCCSM
Australian Community Climate and Earth System Simulator coupled model	ACCESS

2.3. Climate indices

Following the CCI/WCRP/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) we calculated 12 indices to characterize extreme climate events in R using the "RClimDex" open access package (Table 2; Bronaugh, 2019). These 12 indices were used to determine the frequency, duration, and intensity of extreme climate events. ETCCDI indices use a threshold method where days/intensity/durations that were either above or below an absolute value or percentile were used to characterize these indices. The ETCCDI climate indices have been used

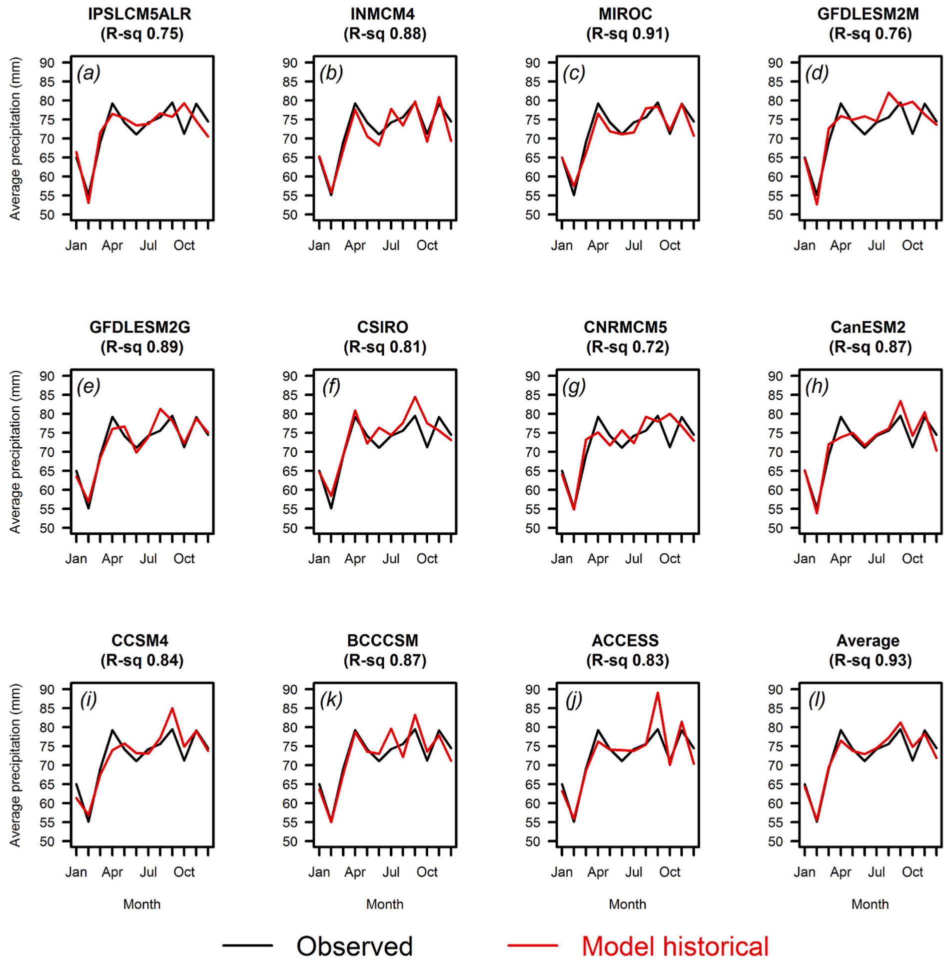

Fig. 2. Seasonal comparison of average precipitation during observed (black line) and simulated historic period (red line) from 1951 to 2005 for each (a-j) GCM and an (l) average of all GCMs.

to detect extreme climate trends in number of studies for a variety of climates, and temporal scales (e.g., Filahi et al., 2016; Moberg et al., 2006; New et al., 2006; Razavi et al., 2016; Vincent et al., 2005; Zhang et al., 2005).

2.4. Statistical methods

The Mann-Kendall test, which is a non-parametric test commonly used to statistically detect upward or downward trends (represented by the Kendall-tau value) in climate and hydrological time series, was used in our study. As this test is non-parametric, there is no assumption on the distribution of the time series. This test was applied to the annual time series of temperature and precipitation for the observed (1951–2013) and projected (2006–2099) periods. Sen's Slope (also called the Theil-Sen robust estimator) was used to determine the magnitude of change of the extreme climate indices. Both the Mann-Kendall and Sen's Slope tests have been used by previous studies to calculate extreme climate trends (e.g., Filahi et al., 2016; Vincent et al., 2005). The statistical tests were conducted using the "Trend", an open access software package in R (Pohlert, 2018).

4. Results

4.1. Climatic changes

4.1.1. Temperature

Temperature anomalies relative to 1961–1990 means were used to detect changes in annual minimum (Tmin; 3 °C) and maximum (Tmax; 12 °C) temperature (shown in Fig. 4a and b). The 1961–1990 baseline period has been suggested by the World Meteorological Organization as the standard for supporting long-term climate change assessments (WMO, 2015), additionally the 1961–1990 baseline period is used by IPCC (2013) to detect climatic changes over time. Temperature anomaly trends for Six Nations showed an overall decadal increase for Tmin (+0.6 °C) and Tmax (+0.8 °C) during the observed period of the study (i.e., 1951–2013). During the projected period, average temperature anomaly is expected to steadily increase under RCP 4.5 emission scenario, where 30-year averages for 2006–2039, 2040–2069, and 2070–2099 periods will increase by 1.6 °C, 2.7 °C and 3.1 °C, respectively for Tmin and 1.6 °C, 2.7 °C, and 3.1 °C, respectively for Tmax. Similarly, 30-years averages under RCP 8.5 emission scenario indicate +1.7 °C, +3.4 °C and +4.9 °C for Tmin and +1.7 °C, +3.5 °C, and +5.1 °C for Tmax. Fig. 4c-h shows seasonal changes in Tmin and Tmax relative to 1961–1990 monthly averages. Observed and projected data suggests that temperature has and will continue to increase during all four seasons. Comparison of monthly values indicated that the largest seasonal change in temperature during the observed period occurred in winter, followed by summer for Tmax and spring for Tmin. In the future, under RCP 4.5 and RCP 8.5 scenarios, Tmax will increase the most from June to October. Tmin is projected to increase the most during December to February period.

4.1.2. Precipitation

Annual changes in total precipitation relative to the 1961–1990

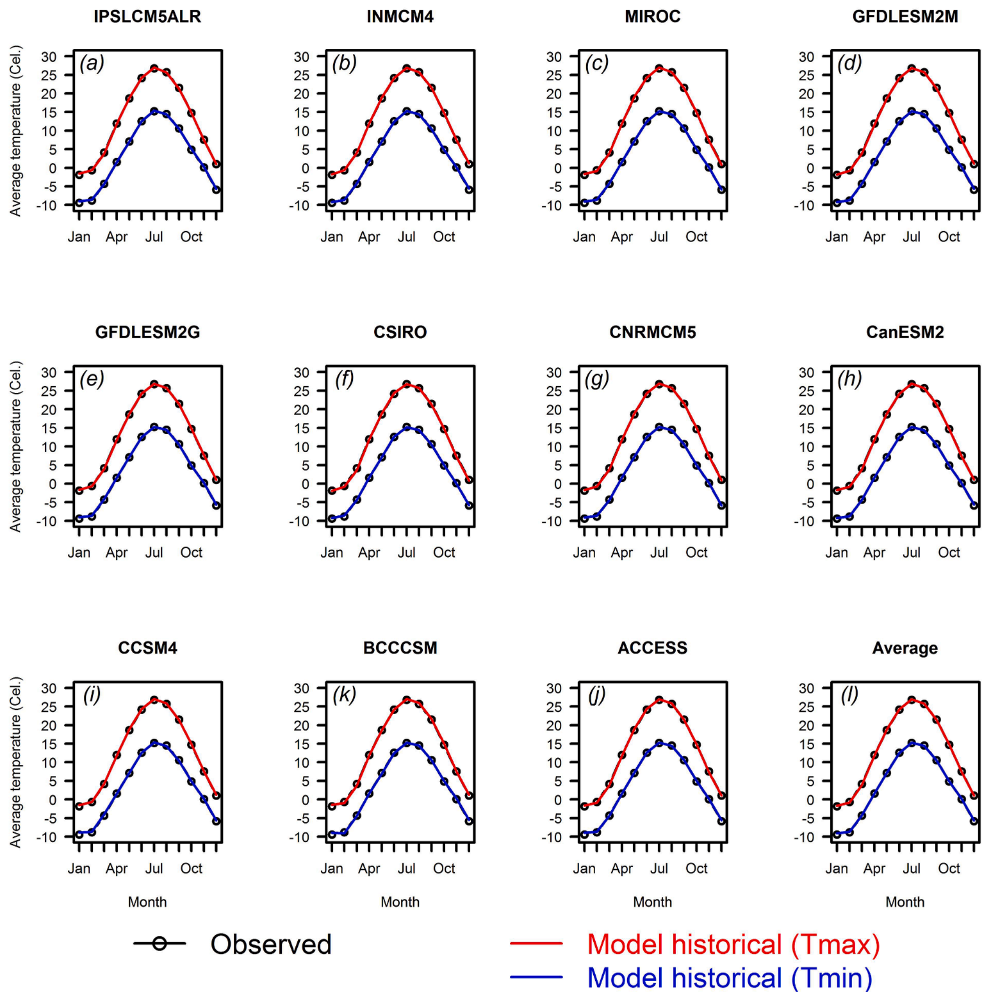

Fig. 3. Seasonal comparison of average minimum and maximum temperature during observed and simulated historic period from 1951 to 2005 for each (a-j) GCM and an (l) average of all GCMs.

baseline period (869 mm for observed period, 835 mm for historic period) are shown in Fig. 5 (a). From 1951 to 2013, observed, average decadal precipitation increased by 42 mm with an average annual rate of increase of 1.6 mm/year. This increasing trend is projected to continue, with average decadal precipitation increasing by 95 mm (RCP 4.5) and 130 mm (RCP. 8.5) by the end of the 21st century. Observed seasonal changes relative to 1961–1990 monthly averages (Fig. 5b) showed a change in precipitation patterns between 1951 and 1979 and 1980–2013. The greatest change in precipitation between these periods occurred during summer and fall, with decline in precipitation occurring from February to April and in August. Future precipitation under RCP 4.5 (Fig. 5c) indicated that precipitation (relative to 1961–1990 average) will increase in winter, early spring, and fall but decrease in summer. Future precipitation under RCP 8.5 will also be similar, with a large increase in winter and spring precipitation (Fig. 5d).

4.2. Extreme climate trends

4.2.1. Trends in temperature extremes

Changes in the frequency and duration of extreme temperature events, and percentage changes between decades as well as the maximum and minimum values of these events are reported in Fig. 6 and Table 3. With respect to the frequency of extreme low temperature events, the annual amount of Ice Day (ID) events fluctuated throughout the observed period, while Frost Night (FrN) events experienced a steady decline. Decadal average of ID events was 49 (1950s) and 52 (2000–2013). The decadal average of FrN events gradually decreased during the observed period with the decadal averages dropping from 141 (1950s) to 132 (2000–2013). Projections of ID and FrN events indicated that both extreme low temperature indices will decrease throughout the 21st century. Decadal averages (2006–2019 to 2090s) of ID are projected to decrease from 47 (multi model range of 28–70) events to 31 (9–57) events under RCP 4.5 and 47 (26–69) events to 12 (2–31) events under RCP 8.5, while FrN are projected to decrease from 128 (105–149) to 107 (79–134) events (RCP 4.5) and 129 (109–152) to 73 (46–103) events (RCP 8.5).

With respect to the frequency of extreme high temperature events, Summer Day (SD) events experienced a smaller overall change than Tropical Night (TN) events, but SD events experienced a greater range of inter-decadal fluctuation. SD events decreased from the 1950s to 1970s, with a total increase of only 1 day between the 1950s and 2000s. Comparatively, TN events increased from 4 (1950s) to 7 (2000–2013) during the observation period. Projections indicated that the increase in extreme high temperature events will accelerate rapidly during the 21st century. Decadal averages (2006–2019 to 2090s) of SD events will increase from 80 (multi model range of 62–99) and 81 (61–101) events to 107 (78–131) and 137 (106–162) events, under RCP 4.5 and 8.5 respectively, and averages of TN will increase from 7 (2–16) and 8 (2–19) events to 20 (10–36) and 56 (24–91) events, under RCP 4.5 and 8.5 respectively.

With respect to the duration of extreme high temperature events, Warm Spell Duration Index (WSDI) events were not as frequent as SD or

Table 2
List of 13 extreme climate indices following ETCCDI.

ID	Name	Description	Unit
Temperature			
FrN	Frost nights	Annual count of days when daily Tmin < 0 °C	Days
ID	Ice days	Annual count of days when daily Tmax < 0 °C	Days
TN	Tropical nights	Annual count of days when daily Tmin > 20 °C	Days
SD	Summer days	Annual count of days when daily Tmin > 25 °C	Days
WSDI	Warm spell duration index	Annual count of days each year that are part of a 'warm spell' (a sequence of 6 or more days in which the daily maximum temperature exceeds the 90th percentile of daily maximum temperature for a 5-day running window surrounding this day during 1961–1990 baseline period	Days
CSDI	Cold spell duration index	Annual count of days each year that are part of a 'warm spell' (a sequence of 6 or more days in which the daily minimum temperature is below the 10th percentile of daily maximum temperature for a 5-day running window surrounding this day during 1961–1990 baseline period	Days
Precipitation			
R10mm	Heavy Rainfall	Annual count of days where daily precipitation ≥ 10 mm	Days
R20mm	Very Heavy Rainfall	Annual count of days where daily precipitation ≥ 20 mm	Days
R99P	Extreme Rainfall	Annual sum of precipitation in days where daily precipitation exceeds the 99th percentile of daily precipitation in the 1961–1990 baseline period	mm
Rx5day	Max 5-day precipitation amount	Annual sum of precipitation for greatest 5-day consecutive precipitation	mm
CDD	Consecutive Dry Days	Maximum number of consecutive days where daily precipitation is < 1 mm	Days
CWD	Consecutive Wet Days	Maximum number of consecutive days where daily precipitation is ≥ 1 mm	Days

TN events during the past study period. Of the past 63 years of observation, WSDI events occurred in only 33 of them. Despite the lack of frequency, the average number of decadal events increased with an overall percentage increase of 31.8% between 1950s and 2000s. This increasing trend is projected to continue into the 21st century, where events per decade will increase from 13 (multi model range of 0–35) and 16 (0–38) (2006–2019) to 47 (6–100) and 139 (46–232) (2090s), under RCP 4.5 and RCP 8.5, respectively. Similarly, observed Cold Spell Duration Index (CSDI) events occurred infrequently during the observed period. Between 1951 and 2013, there were a total of seven events (1958, 1960, 1964, 1978, 1979, 1984, and 1989) with the average duration of the events being 6.57 days. Under RCP 4.5 and RCP 8.5, the frequency of CSDI events is projected to decline, with the number approaching or equalling to zero by the end of this century.

4.2.2. Trends in precipitation extremes

The evolution of extreme precipitation indices, and percentage changes between decades as well as the maximum and minimum of events are reported in Fig. 7 and Table 4. Both Heavy Rainfall (R10mm) and Very Heavy Rainfall (R20mm) events experienced slight changes in their frequency, with both indices undergoing large inter-annual fluctuations during the observed period. Decadal averages of R10mm events increased from 26 (1950s) to 27 (2000–2013) (+4.5% change), and averages of R20mm decreased from 7 events (1950s) to 6 events (2000–2013) (-5.1% change). With respect to the intensity of precipitation, percentage change between the decades indicated that Extreme Rainfall (R99P) events decreased throughout the observed period except for the 1950s to 1960s and 1980s to 1990s when precipitation increased by 15% and 91%, respectively. The maximum amount of R99P events occurred during the 1990s with a single 176 mm rainfall event occurring in 1999. Maximum 5-day Rainfall (Rx5day) events also experienced large inter-annual fluctuations with percentage decreases occurring in 1950s to 1960s and 1980s to 1990s.

The frequency of heavy precipitation events is projected to increase slightly by the end of the century from their 2006–2019 averages (difference of 2 (0.5–0.4) to 3 (2–4) events for R10mm and 1 to 2 (1.5–3) events for R20mm); however, the intensity of precipitation will experience a much greater increase. Trends in precipitation intensity are projected to increase throughout the 21st century, with R99P events increasing from 68 (multi model range of 2–166) mm and 71 (2–192) mm (2006–2019 average) to 82 (10–180) mm and 116 (15–266) mm (2090s) for RCP 4.5 and RCP 8.5, respectively. Rx5day events increased from 68 (47–98) mm and 69 (49–93) mm (2006–2019 average) to 72 (51–106) mm and 78 (55–116) mm (2090s) for RCP 4.5 and RCP 8.5 scenarios, respectively. With respect to the duration of extreme precipitation, observed data suggests that conditions became wetter showing a decrease in CDD and an increase in CWD events. Projections indicated that CWD events will increase under both RCP 4.5 and RCP 8.5 scenarios, while CDD events will remain relatively unchanged through the 21st century.

4.3. Statistical trends

Statistical analysis (Table 5) of observed extreme temperature trends indicated that heat related extremes (SD, TN, and CSDI) have increased (TN with statistical significance) while cold related extremes (ID, FrN, and CSDI) have decreased (FrN with statistical significance) between 1951 and 2013. As for precipitation related extremes (R10mm, R20mm, R99P, Rx5day, CWD, CDD), all have experienced statistical increases in frequency and duration (CWD with statistical significance) except for Rx5day and CDD which saw an overall decrease in frequency between 1951 and 2013. These trends within the observed data will continue into the projected period (2006–2099), except for CDD and Rx5day which will both increase in the future. Additionally, all projected indices except for CDD (RCP 4.5 and 8.5) and CWD (RCP 4.5) showed statistical significance in the direction of their trend.

4. Discussion

4.1. Observed trends

The findings from this study suggest that the overall climate trends in Six Nations area showed a tendency of increasing warm and wet conditions throughout the 20th century. These trends were consistent with other studies in the literature looking at changes in climatic conditions and extremes in other regions in Southern Ontario. For example, Soulis et al. (2016) found that between 1960 and 2010 sub-daily and daily storms increased in Ontario. Anderson and Gough (2017) analysis reflected that between 1841 and 2015 extreme cold temperature decreased while extreme warm temperature increased in the Greater Toronto Area. The study by Wazneh et al. (2017) which used the same observed dataset and indices for a large area of Southern Ontario found an overall decrease in the frequency of cold temperature extremes and an increase in the frequency of warm temperature extremes, as well as increase in precipitation and precipitation extremes across the region from 1951-2013. Wazneh et al. (2017) also observed that Southern Ontario nighttime warming is greater than daytime warming. However, in contrast, observed data for Six Nations region of Ontario showed that daytime warming increased at a greater rate (SD Sen's slope of 0.105) than nighttime warming (TN Sen's slope of 0.073). These trends are likely associated with larger impacts of global warming, but the inter-annual and inter-decal fluctuations noted in the observed data may be caused by large-scale climate variability modes. Shabbar and Khandekar (1996) found that El Nino episodes had a positive correlation with

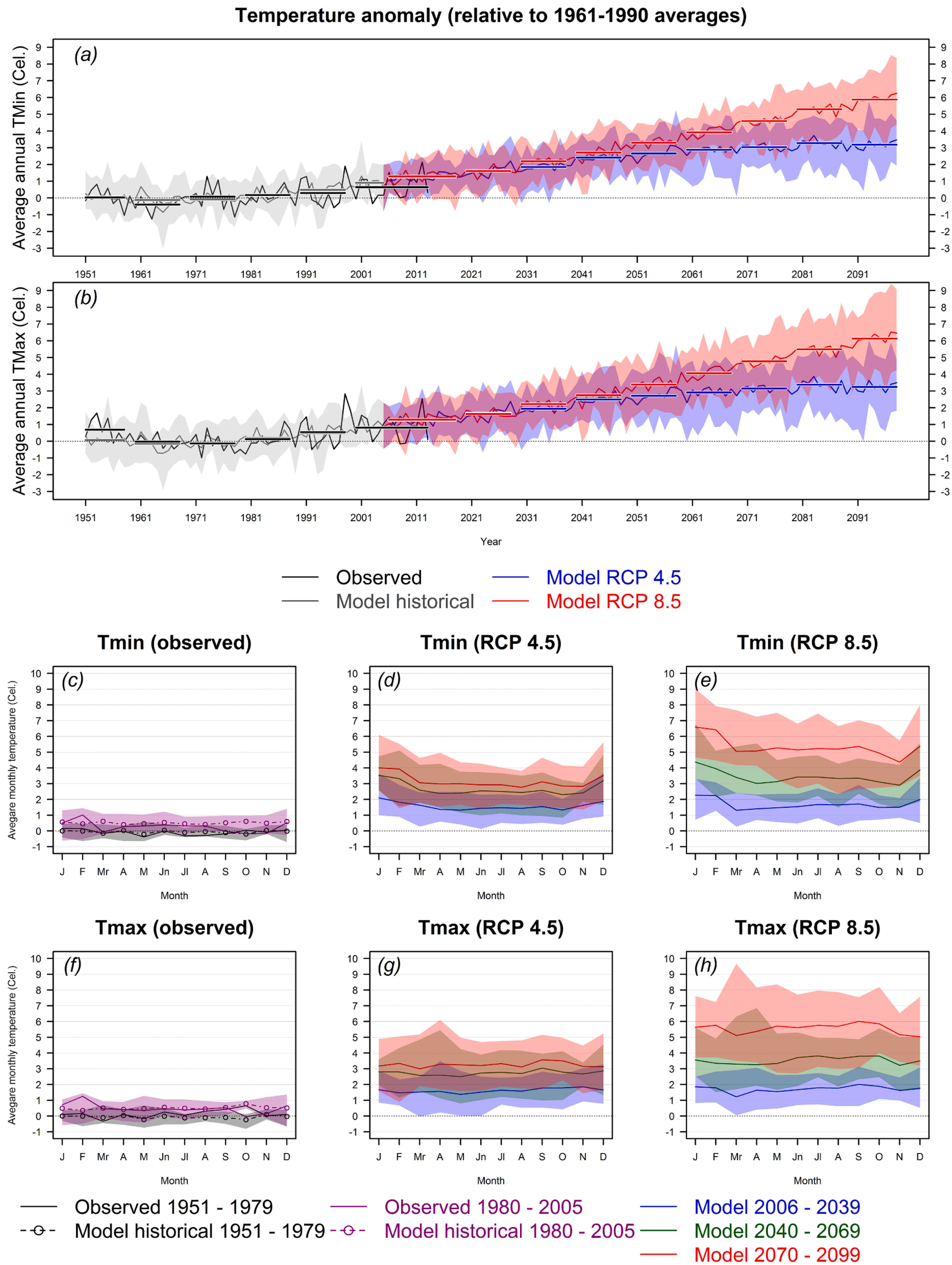

Fig. 4. (a-b) Change in temperature relative to 1961–1990 baseline for observed temperature (bolded black line), simulated temperature during historic period (bolded grey line), and projected temperature under RCP 4.5 (bolded blue) and RCP 8.5 (bolded red) scenarios for (a) minimum temperature and (b) maximum temperature. Multi model annual range represented by shaded colours and decadal averages represented by bolded horizontal lines. Change in monthly (c-e) minimum and (f-h) maximum temperature based on 30-year periods with multi model annual range (shaded colours). Observed seasonal temperature in bolded black (1951–1979) and purple (1951–2013) and simulated seasonal temperature during historic period in dotted dashed black (1951–1979) and purple (1980–2005). Projected seasonal temperature as bolded blue (2006–2039), bolded green (2040–2069), and bolded red (2070–2099) lines.

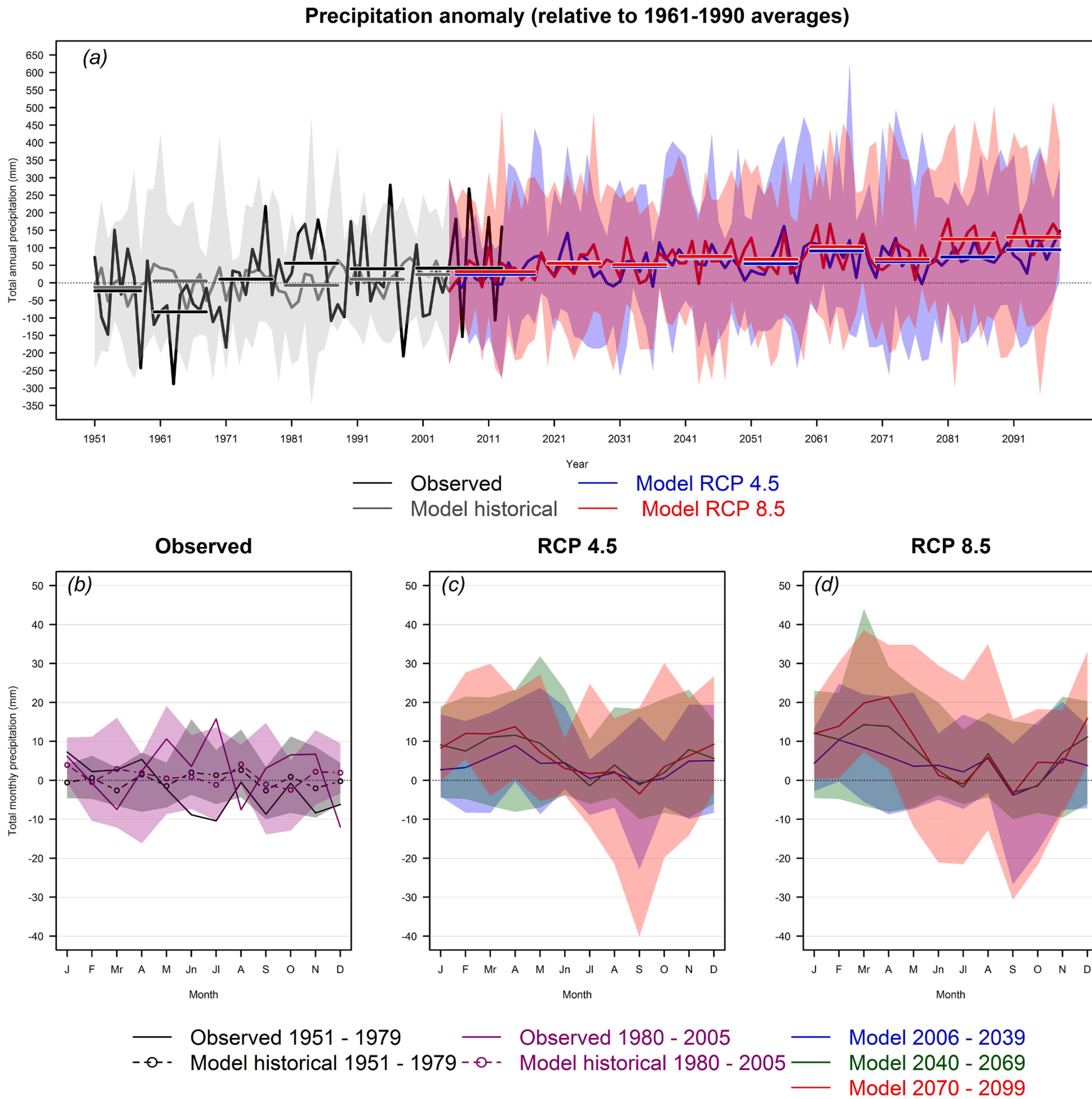

Fig. 5. (a) Change in annual precipitation relative to 1961–1990 baseline for observed precipitation (bolded black line), simulated precipitation during historic period (bolded grey line), and projected precipitation under RCP 4.5 (bolded blue) and RCP 8.5 (bolded red). Multi model annual range represented by shaded colours and decadal averages represented by bolded horizontal lines. Change in monthly precipitation based on 30-year periods with multi model annual range (shaded colours). (b) Observed seasonal precipitation in bolded black (1951–1979) and purple (1951–2013) and simulated seasonal temperature during historic period in dotted dashed black (1951–1979) and purple (1980–2005). (c and d) projected seasonal temperature in bolded blue (2006–2039), bolded green (2040–2069), and bolded red (2070–2099).

temperature anomalies across Canada during late fall to early spring months (1946–1994). Similar results for El Nino have been reported in Bonsal et al. (2001) for Eastern Canada. For precipitation, negative patterns were noted in precipitation anomalies of the first winter following El Nino episodes from British Columbia to the Great Lakes from 1911 to 1994 (Shabbar et al., 1997). Additionally, while Six Nations has retained much of its original Carolinian forest, the surround areas have undergone significant land use and land cover change. Much of the region has been converted to either agricultural land or small urban settlements, which may have had an impact on the energy balance, evapotranspiration, and hydrological cycle of the region. These impact may provide possible or partial explanation for the change in precipitation patterns between the 1951–1979 and 1980–2013.

4.2. Impacts of future trends

Future predictions of climatic conditions and extremes indicate that decadal average temperature may increase by 3.2 to 6.2 °C (Tmax) 3 to 6 °C (Tmin) by end of 21st century (relative to 1961–1990 average). For precipitation, the increase is in the order of 6.4 to 10.6 % (decadal average) between 2006 and 2019 and 2090s. Comparison of seasonal temperature and precipitation value suggest that winter rainfall may increase due to changes in winter precipitation and winter temperatures. This is supported by projections of cold related extremes which showed an overall decrease in the frequency of ID and FrN events (i.e., warming winter trend). These changes may result in increased frequency and intensity of winter-spring flooding in McKenzie and Boston Creeks due

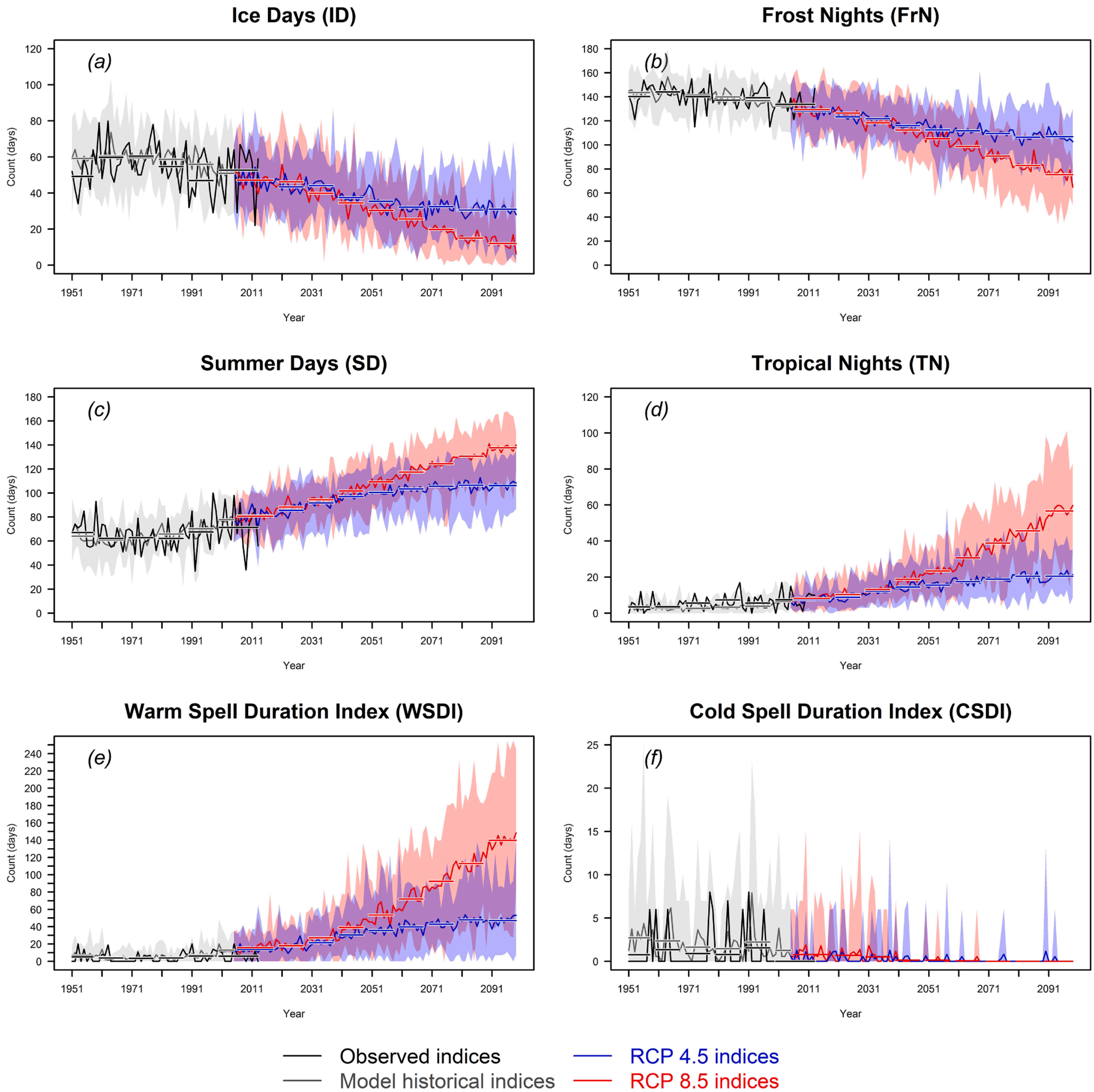

Fig. 6. Time series of annual extreme temperature indices for (a) Ice Days (ID), (b) Frost Nights (FrN), (c) Summer Days (SD), (d) Tropical Nights (TN), (e) Warm Spell Duration Index (WSDI), and (f) Cold Spell Duration Index (CSDI). Observed results are bolded black, simulated model results during historic period are bolded grey, projected RCP 4.5 results are bolded blue, and projected RCP 8.5 results are bolded red. Multi model annual range represented by shaded colours and decadal averages represented by bolded horizontal lines.

to the aforementioned factors as well as the projected increase in extreme precipitation (R10mm, R20mm, R99P and Rx5day) and winter precipitation. Conversely, summer monthly precipitation is projected to decrease while seasonal temperatures are projected to continue to increase along with WSDI events, this may result in longer and more frequent droughts and heat waves. Additionally, a decrease in summer precipitation may affect the recharge of the McKenzie Creek subwatershed aquifer which is used for irrigation by farmers in the region, as well as the flow rates of the McKenzie Creek (Wong, 2011). Also, the overall warming trend and increase in the duration of WSDI events may pose a significant threat to the health and well-being of the community. As seasonal temperatures rise the prevalence of tick-borne diseases will increase. Nelder et al. (2018) found that in 2017, there were 959 probable and confirmed cases of Lyme diseases in Ontario. This was a nearly three times increase from the 2012–2016 average of 313 cases. A possible cause for this was the increase in the number of days above 0 °C and milder winters. Additionally, studies on the effect of temperature rise on human health and wellbeing in Ontario have indicated that a 5 °C increase in temperature increases mortality by 2.5% (Chen et al., 2016), and hospitalization for coronary heart disease by 6.0% (Bai et al., 2018). The future climate trends presented in our study are largely consistent with similar projections in Southern Ontario (Wazneh et al., 2019).

Table 3
Summary table of results for observed extreme low temperature indices. (Top) Percentage change between decadal averages from 1950s to 2010s (green coloured cells indicate positive change, and red indicate negative change). (Bottom) Annual maximum and minimum result for each index and the corresponding year(s).

		ID	FrN	SD	TN	WSDI	CSDI
Decadal percentage change	*50s - 60s*	21.1%	2.0%	-10.1%	-16.7%	-23.5%	80.0%
	60s - 70s	0.3%	-3.2%	-1.9%	40.5%	-8.8%	16.7%
	70s - 80s	-7.4%	-1.0%	1.1%	32.7%	32.3%	-7.1%
	80s - 90s	-17.1%	-0.1%	11.1%	-17.4%	61.0%	7.7%
	90s - 00s	13.2%	-3.1%	2.9%	30.3%	-11.3%	-100.0%
	50s - 00s[a]	5.5%	-5.3%	1.8%	67.1%	31.8%	-100.0%
Max/Min number of events	*Max (Year)*	80 (1963)	159 (1978)	100 (1998)	17 (1988, 2002)	20 (1953, 1991, 2005)	8 (1991)
	Min (Year)	22 (2012)	115 (1973, 1998)	35 (1992)	0[b]	0[c]	0[d]

[a]00 s covers 2000–2013
[b]1951, 1956, 1992, 2000
[c]all years except: 1953, 1955, 1957, 1961, 1962, 1963, 1973, 1975, 1976, 1977, 1981, 1982, 1987, 1988, 1989, 1991, 1995, 1997, 1989, 1999, 2000, 2001, 2005, 2006, 2007, 2008, 2010, 2012
[d]all years except: 1958, 1960, 1964, 1978, 1979, 1984, 1989, 1991, and 1996

4.3. Future planning

The climate information and data produced by this study can serve as resource for future community resilience planning and resource allocations strategy for ensuring a climate secure future of the Six Nations community. Six Nations recognizes that climate change and environmental disasters (for example, floods) pose a threat to the security of the community, as such they have outlined key objectives in their Community Plan to “adapt to climate change and reduce [its] impact” (SNGRDC, 2019, p. 24). Short term (2019–2024) objectives of Six Nations’ plan is to conduct a community study of climate change to better understand the impacts climate change will have on the built environment, integrate climate change into their emergency response plans, and inform community members of the risk of climate change. These actions are either in the planning stages or have yet to be started, Therefore our analysis and results will be able to assist planners and the community leaders in accomplishing their goals.

The community can use our findings and data in many ways. For example, our results can be used for cross-reference or validation of past extreme events that community experienced, which would help to better understand the scope of future extreme event impacts and associated risks. A good example would be cross referencing Hurricane Hazel’s precipitation to future extreme rainfall (R99P) or maximum 5-day rainfall (Rx5day) and exploring potential impacts and vulnerability of the community to such events in the future. Alternatively, planners and decision makers can assess how changes in seasonal temperature and precipitation patterns, as well as duration of extreme high temperature events (WSDI) may affect agricultural yields and economic profitability, and whether alternative climate resilient crops and agricultural practices need to be considered. Our study also provides quantitative information and rates of increase and decrease of key indicators of extreme climate. Therefore, this data can directly be used by the community for environmental risk analysis and planning purposed. For example, examining the increase in number of Consecutive Wet Days (CWD), which may place greater stress on personal and public infrastructure (e.g. basement flooding, road damage), or warm days (SD), which has health and agricultural productivity implications, can assist to better prepare for their associated impacts.

5. Conclusion

As carbon dioxide and other greenhouse gas emissions continue to increase, it is becoming more evident that the global climate will not stabilize in coming decades. The bio-physical changes that will result from this increase in global surface temperature will be of a magnitude greater than communities and states had previously planned. The production of climate services that provide accurate, high-resolution climate information and data are, therefore, essential for the decision makers and planners to make plans to deal with extreme climate events and take measures to adapt to these changes. This is especially important for Indigenous communities due to the disproportionate nature at which they are affected by climate change and extreme weather events.

This is the first study where ETCCDI indices were used to analyze the past and projected impacts of climate change and the frequency of extreme climate events on an Indigenous community in Canada. This study presented a trend analysis of climatic changes and extreme weather events (observed and projected) for Six Nations of the Grand River reserve, the largest First Nations community in Canada. A set of 12 ETCCDI indices were calculated from 1951 to 2099 using observed gridded Natural Resources Canada meteorological dataset (NRCANmet) and simulated data from 11 downscaling Coupled Model Intercomparison Project (CMIP5 framework) models. The key findings suggest that:

- The climate in the area of interest has gotten wetter and warmer with total annual precipitation increasing by 42 mm from 1951 to 2013.
- The frequency and duration of extreme events has increased from 1951 to 2013, while extreme low temperature events have decreased. The frequency, intensity, and duration of observed extreme precipitation has increased from 1951 to 2013, while the duration of dry periods has decreased.
- Future climate simulations indicate that air temperature will increase by 3 to 6 °C and precipitation will increase by 95 to 130 mm (RCP 4.5 and 8.5 averages) by the end of the 21st century. Seasonal precipitation changes indicate increase in winter, early spring precipitation, and fall, and decrease in late spring and summer precipitation.

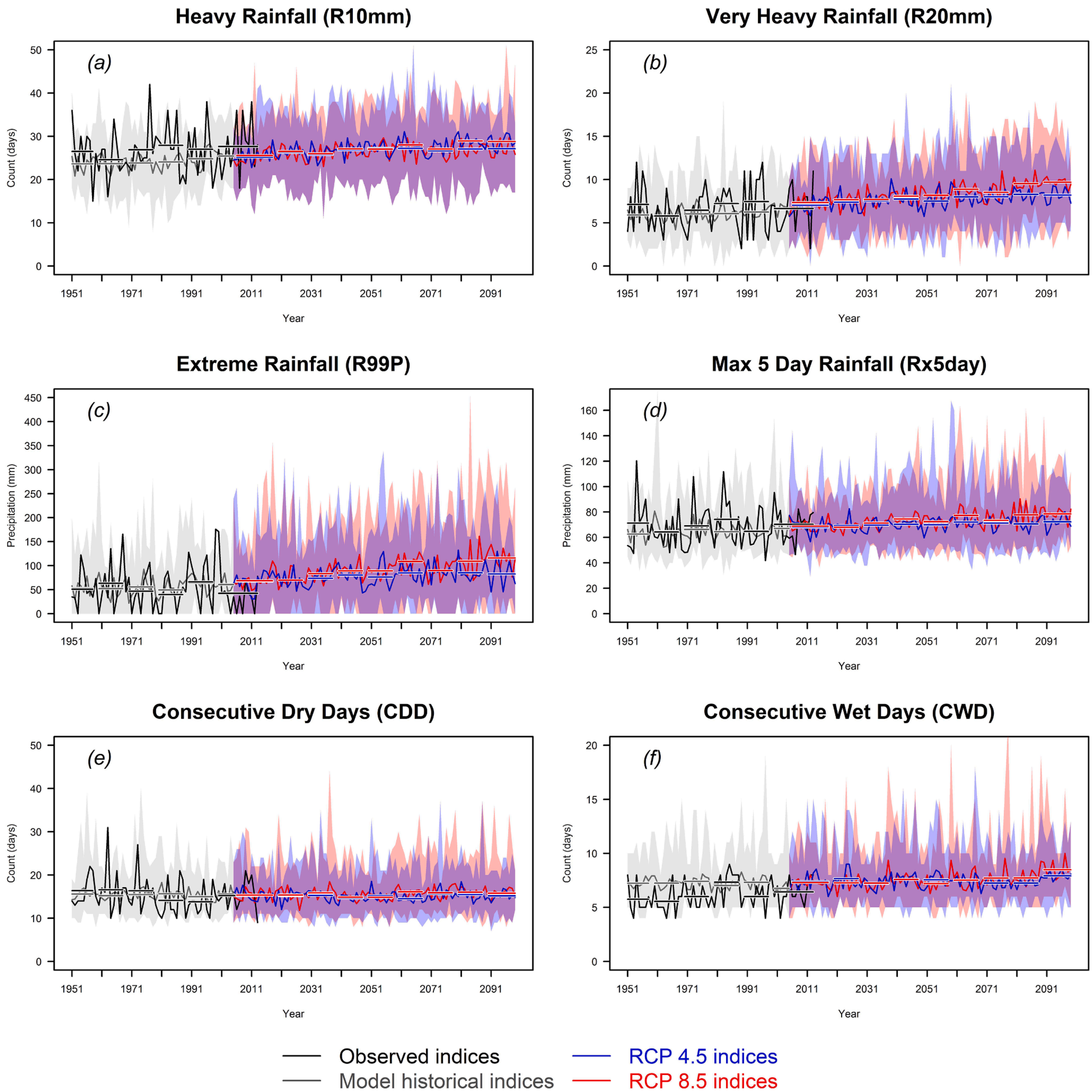

Fig. 7. Time series of annual extreme precipitation indices. (a) Heavy Rainfall (R10mm), (b) Very Heavy Rainfall (R20mm), (c) Extreme Rainfall (R99P), (d) Maximum 5-day Rainfall (Rx5day), Consecutive Dry Days (CDD), and Consecutive Wet Days (CWD). Observed results are bolded black, simulated model results during historic period are bolded grey, projected RCP 4.5 results are bolded blue, and projected RCP 8.5 results are bolded red. Multi model annual range represented by shaded colours and decadal averages represented by bolded horizontal lines.

- Future extreme climate trends indicate increase in extreme high temperature events, and a decrease in extreme low temperature events, with RCP 8.5 projecting a greater overall change than RCP 4.5. The frequency, intensity, and duration of extreme rainfall events will increase in future, however, the difference between RCP 4.5 and 8.5 will not be as pronounced.
- There will likely be an increase in the frequency and intensity of winter-spring flooding events as a result of future increases in winter precipitation and warmer temperatures.
- Drought and heatwaves may become more prevalent and intense as a result of projected increases in summer temperature and extreme high temperature events, and decreases in summer precipitation. Additionally, ecosystem health may also be affected due to lower flow rates in the McKenzie Creek during summer months.

The trends outlined in this study will help Six Nations to prepare for the threats from increased flooding, drought, and heatwaves to the wellbeing and safety of community members. It is therefore suggested that stakeholders and community leaders consider these findings for future climate change adaptation planning and extreme weather events preparedness.

Practical implications

Global climate impact assessments provide essential overviews of

Table 4
Summary table of results for observed extreme precipitation indices. (Top) Percentage change between decadal averages from 1950s to 2010s (green coloured cells indicate positive change, and red indicate negative change). (Bottom) Annual maximum and minimum result for each index and the corresponding year(s).

		R10mm	R20mm	R99P	Rx5day	CCD	CWD
Decadal percentage change	*50s - 60s*	-7.4%	-18.6%	15.0%	-11.7%	2.3%	-1.2%
	60s - 70s	11.0%	8.8%	-26.1%	9.3%	-3.6%	7.1%
	70s - 80s	-0.7%	8.1%	-11.4%	4.6%	-14.4%	18.3%
	80s - 90s	-1.9%	10.4%	91.4%	-10.2%	1.5%	-12.7%
	90s - 00s[1]	4.3%	-10.2%	-45.0%	8.8%	9.5%	3.7%
	50s - 00s[a]	4.5%	-5.1%	-20.6%	-1.4%	-6.2%	13.4%
Max/Min number of events	*Max (Year)*	42 (1977)	12 (1954, 1996)	176.1 (1999)	120.2 (1954)	31 (1963)	9 (1985)
	Min (Year)	15 (1958)	2 (1989, 2012)	0[b]	41.9 (1997)	9 (2013)	4[c]

[a] 00 s covers 2000–2013
[b] 1953, 1960, 1965, 1971, 1974, 1978, 1980, 1981, 1986, 1994, 1998, 2004, 2006, 2008, 2012
[c] 1953, 1964, 1967, 1997, 2002

Table 5
Summary tables of statistical results from Mann-Kendall and Sen's Slope tests (95% confidence interval). Green colours cells indicate an increasing trend, red coloured cells indicate a decreasing trend.

	Kendall's Tau (Sen's Slope)		
Data	**Observed**	**RCP 4.5 average**	**RCP 8.5 average**
Timeframe	1951-2013	2006-2099	2006-2099
ID (days/year)	-0.016 (0.000)	**-0.648 (-0.219)**	**-0.840 (-0.461)**
FrN (days/year)	**-0.230 (-0.170)**	**-0.714 (-0.279)**	**-0.861 (-0.680)**
SD (days/year)	0.081 (0.105)	**0.755 (0.323)**	**0.898 (0.697)**
TN (days/year)	**0.226 (0.073)**	**0.749 (0.173)**	**0.915 (0.574)**
WSDI (days/year)	0.154 (0.000)	**0.757 (0.455)**	**0.888 (1.510)**
CSDI (days/year)	-0.724 (0.000)	**-0.220 (0.000)**	**-0.482 (0.000)**
PRCP_TOT (mm/year)	**0.157 (1.624)**	**0.257 (0.612)**	**0.411 (0.966)**
R10 (days/year)	0.071 (0.022)	**0.230 (0.022)**	**0.374 (0.038)**
R20 (days/year)	0.077 (0.000)	**0.282 (0.014)**	**0.485 (0.028)**
R99P (mm/year)	0.028 (0.000)	**0.199 (0.203)**	**0.435 (0.571)**
Rx5day (mm/year)	-0.088 (0.113)	**0.197 (0.051)**	**0.353 (0.123)**
CDD (days/year)	-0.059 (0.000)	0.004 (0.000)	0.133 (0.009)
CWD (days/year)	**0.212 (0.000)**	0.078 (0.002)	**0.289 (0.009)**

warming trends at large scales. While these global assessments are essential for understanding regional and sub-national changes in the climate, they are limited in their ability to provide detailed information on the impacts of climate change on local communities (Kotamarthi et al., 2019). Local communities are ultimately where the impacts of climate change are most felt and where adaptation to climate change is needed the most. And so, providing high spatial resolution data and quantitative climate information is essential for local disaster risk assessment, decision making and developing policies to adapt to climate change. The need of high spatial resolution climate information was highlighted during the Climate Services for Disaster Risk Reduction workshop (2018) as useful component of climate change adaptation planning and disaster risk reduction preparedness (Street et al., 2019). This is further supported by a survey of Ontario climate information users where data end-users preferred high spatial resolution data from municipal/community level models for their decision-making (Morand et al., 2015). Our study provides this high-resolution downscaled past and future climate and extreme weather information and data that will fulfill the needs of the Six Nations of the Grand River reserve, the largest Indigenous community in Canada. Our study results will serve as a useful resource in future planning efforts, given that extreme precipitation events and long-term temperature and precipitation changes are listed as the top three hazards of concern by the Ontario climate information and data end-users (Morand et al., 2015), and that Indigenous communities are disproportionally more affected by climate change and extreme weather events (Public Safety Canada, 2019). Our results and quantitative information will help to understand the impacts of climate change, prepare for more frequent and severe extreme weather events, and educate and inform community members about the risks of climate change, all of which are climate change goals outlined in the Six Nations Community Plan (SNGRDC, 2019, p. 13). Therefore, our study will be very useful for Six Nations' decision makers and community leaders as they move forward with their Community Plan to deal with climate change impacts.

CRediT authorship contribution statement

Tariq A. Deen: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **M. Altaf Arain:** Conceptualization, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Olivier Champagne:** Conceptualization, Writing – review & editing. **Patricia Chow-Fraser:** Writing – review & editing, Supervision. **Nidhi Nagabhatla:** Writing – review & editing, Supervision. **Dawn Martin-Hill:** Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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