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Key Points:

- Projected IDF curves are developed using a regional climate modeling approach
- Intensities of rainfall extremes are projected to increase over time
- Intense rainfall events are likely to occur more frequently

Supporting Information:

- Readme
- Table S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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Projected increases in intensity and frequency of rainfall extremes through a regional climate modeling approach

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Abstract Global warming is changing the hydrological cycle in multiple ways such as increased cloudiness, latent heat fluxes, and intense precipitation events. How extreme rainfall events will be influenced by the changing climate is becoming one of the most important problems for hydrological risk analysis and engineering design. In this study, a regional climate modeling approach based on the Providing REgional Climates for Impacts Studies modeling system is proposed for investigating the potential impacts of climate change induced by increased greenhouse gases on the intensity and frequency of extreme rainfall events in the context of Ontario, Canada. An ensemble of high-resolution climate projections is first developed under both current and future forcing conditions. Validation of the ensemble simulations is then conducted through comparing the simulated rainfall annual extremes for 1960–1990 to the observed ones. Following that, the rainfall projections for future periods are used to develop projected intensity-duration-frequency curves and their plausible changes in 2030s, 2050s, and 2080s for the City of Toronto. The results suggest that intensities of rainfall extreme events versus various durations with different return periods are all likely to increase over time: [5, 17]% in 2030s, [11, 22]% in 2050s, and [25, 50]% in 2080s. Such a consistent increase would lead to an overall uplift in the exceedance values of rainfall intensity of extreme events, implying that intense rainfall events are likely to occur more frequently in the future. In addition, more significant changes in the rainfall intensity are projected for extreme events with longer return periods at all given durations.

1. Introduction

Extreme weather and climate events, such as floods, droughts, rainstorms, and wind gusts, have received increased attention in the past few decades, due to the often large economic loss, fatalities, as well as many other severe consequences for human society [*Easterling et al.*, 2000a; *McMichael et al.*, 2006]. This is especially true for Canada, where severe floods have frequently struck its major cities in recent years and caused billions of dollars in damage. For example, the extreme precipitation events in Calgary and Toronto in June 2013 have been recorded as the largest natural disasters in Alberta's and Ontario's history, respectively, and the insurance damages caused by these two events have constituted the first and third largest natural insured catastrophes in Canadian history. Recent modeling efforts suggest that there will be significant changes in these extreme events in the future either due to natural climate fluctuations or greenhouse gas (GHG)-induced warming [e.g., *Easterling et al.*, 2000b; *Gao et al.*, 2006; *Kharin et al.*, 2013; *Meehl et al.*, 2000; *Peterson et al.*, 2012; *Tebaldi et al.*, 2006; *Zhang et al.*, 2001]. Planning for such changes based on our latest knowledge of the frequency of extreme weather and climate events has become a major focus of both policy makers and development practitioners.

As a consequence of global warming, the hydrological cycle has been amplified in the form of increased cloudiness, latent heat fluxes, and intense precipitation events and flooding [*Knapp et al.*, 2008]. Assessing the potential changes in extreme precipitation events is becoming one of the most important practical issues for hydrological risk analysis and engineering design. The intensity-duration-frequency (IDF) relationship of the rainfall extremes is usually summarized in the evaluation process and widely used as a convenient tool for understanding the characteristics of extreme rainfall events at given locations [e.g., *Ben-Zvi*, 2009; *Koutsoyiannis et al.*, 1998; *Langousis and Veneziano*, 2007; *Mailhot et al.*, 2007; *Veneziano and Furcolo*, 2002]. However, previous studies on IDF curves are largely based on the observational data at given weather stations, and the curves are not often updated until new observations are available. Moreover, the development of IDF curves relies on an assumption of rainfall series stationarity that the intensity and frequency of extreme hydrological events remain unchanged over time [*Mailhot et al*., 2007]. In fact, such assumptions may not be appropriate in the context of climate change [*Chen and Rao*, 2002].

In recent years, the projections of global climate models (GCMs) are often used to estimate the effects of climate change on the intensity and frequency of extreme rainfall events under different GHG emission scenarios [e.g., *Allan and Soden*, 2008; *Fowler et al*., 2007; *Fowler and Kilsby*, 2003]. However, the spatial resolution of GCM outputs is too coarse to capture regional variations in precipitation which are closely related to the local topography and surface characteristics [*Wang et al*., 2014b]; furthermore, the size of precipitation storm is usually much smaller than the spatial resolution of large-scale climate models. Downscaling to the GCM outputs is therefore needed to develop high-resolution climate projections at regional scales with considerations of local characteristics using either statistical or dynamical approaches. Statistical downscaling mainly involves developing a quantitative relationship between large-scale atmospheric variables and local-scale weather indicators such as temperature and precipitation [*Prudhomme et al*., 2002; *Wang et al*., 2013; *Wilby and Wigley*, 1997]. The obvious drawback of statistical technique is that it cannot simulate the complex interactions among the various components of the local climate system, especially the dynamics of small-scale storms. By contrast, dynamical downscaling is usually implemented by nesting a regional climate model (RCM) into GCMs, such that the interactions can be simulated in a physically based way [*Feser et al*., 2011; *Rummukainen*, 2010]. This is largely because RCMs are developed using the same laws of physics as described in GCMs to account for the sub-GCM grid-scale processes with more details (such as mountain ranges, coastal zones, and details of soil properties) [*Feser et al*., 2011]. As a result, RCMs are widely used to develop high-resolution climate projections to help assess the potential changes in local precipitation extremes in the context of climate change [e.g., *Buonomo et al*., 2007; *Eden et al*., 2012; *Frei et al*., 2006; *Herrera et al*., 2010; *Huntingford et al*., 2003; *Wang and Zhang*, 2008; *Zhang et al*., 2006].

Therefore, in this study, a regional climate modeling approach will be proposed to investigate how the intensity and frequency of extreme rainfall events will be influenced by the changing climate within a regional context. Specifically, our research will focus on the Province of Ontario, Canada. We first develop an ensemble of high-resolution climate projections at a resolution of 25 km using the Providing REgional Climates for Impacts Studies (PRECIS) modeling system, which is driven by a set of boundary conditions from a perturbed physics ensemble (PPE) provided by UK Met Office Hadley Centre. The Gumbel extreme value distribution is then adopted to develop projected IDF curves at PRECIS grid point scales under both current and future forcing conditions. The projected IDF curves for the entire province are developed and made available at Ontario Climate Change Data Portal (http://ontarioccdp.ca), and this paper mainly presents analyses on the projected IDF curves for the City of Toronto. The PRECIS projections are divided into four 31 year periods: 1960–1990 (namely, baseline period), 2015–2045 (2030s), 2035–2065 (2050s), and 2065–2095 (2080s). The simulated rainfall annual extremes for the baseline period are compared with the observed extremes at 12 gauged weather stations to validate the performance of the PRECIS ensemble; the rainfall projections for future periods are then used to develop projected IDF curves and to calculate their changes relative to the baseline period.

2. Methodology

2.1. Regional Climate Modeling

Dynamical downscaling to the large-scale projections of GCMs is usually implemented with the aid of high-resolution RCMs to represent the detailed processes, interactions, and feedback between the components of a local climate system. In this study, the PRECIS regional climate modeling system will be used to develop high-resolution climate projections at regional scales. The PRECIS is a flexible, easy-to-use, and computationally inexpensive RCM designed to provide detailed climate scenarios [*Wilson et al*., 2011]. It can be applied easily to any area of the globe to generate detailed climate change projections, with the provision of a simple user interface as well as a visualization and data processing package. The PRECIS is able to run at two different horizontal resolutions: 0.44° (approximately 50 km) and 0.22° (approximately 25 km), with 19 vertical levels using a hybrid coordinate system (a combination of σ coordinate and pressure-based coordinate), and its output variables are available at various temporal scales (i.e., annual, seasonal, monthly, daily, and hourly).

Owing to its powerful capability in regional climate modeling, the PRECIS model has been widely used for many climate change impact studies in the past few years [e.g., *Akhtar et al.*, 2008; *Bhaskaran et al.*, 2012; *Buonomo et al.*, 2007; *Cerezo-Mota et al.*, 2011; *Chenoweth et al.*, 2011; *Dulièère et al.*, 2011; *Karmalkar et al.*, 2011; *Shahgedanova et al.*, 2010; *Taylor et al.*, 2011; *Wang et al.*, 2014a, 2014c].

Climate simulation with a single model only provides us with information about one possible outcome of future climate changes, but it does not provide us with more information about how confident we should be in those changes [*Bellprat et al.*, 2012]. Ensemble modeling approaches through either multimodel ensemble or PPE are widely used to explore the range or spread of climate projections, which enables us to gain a better understanding of the uncertainties associated with the projections. In this study, we use a Hadley Centre Coupled Model version 3 (HadCM3)-based PPE (known as Quantifying Uncertainty in Model Predictions (QUMP)) under the Special Report on Emission Scenarios (SRES) A1B emissions scenario to drive the PRECIS model. The QUMP consists of 17 members and is developed by the Hadley Centre to allow users to generate an ensemble of high-resolution regional climate projections [*McSweeney et al.*, 2012]. Downscaling the 17-member PPE ensemble with PRECIS would require very large inputs of computing resources, data storage, and data analyses. In order to explore the range of uncertainties while minimizing these requirements, we select 5 members (i.e., HadCM3Q0, Q3, Q10, Q13, and Q15) from the QUMP ensemble according to the Hadley Centre's recommendation [*McSweeney and Jones*, 2010]. HadCM3Q0 is first selected as it is the standard, unperturbed model using the original parameter settings as applied in the atmospheric component of HadCM3. Selection of the remaining 4 members is based on (a) their performances in simulating the climate of the present day, to ensure that the selected members can represent the climate of the region of interest realistically and (b) the range or spread of future outcomes, in order to ensure that the selected members can sample the full range of outcomes simulated by the 17-member ensemble [*McSweeney and Jones*, 2010]. In this study, we run the PRECIS experiments at its highest horizontal resolution (i.e., 25 km) with a lengthy simulation starting from 1950 and ending at 2099.

Here we focus on studying the effects of climate change on rainfall IDF curves in the context of Ontario, Canada, and the domain setup for the PRECIS ensemble runs is shown in Figure 1. As the second largest province in Canada, Ontario is located in the east central region of Canada and covering more than 1×10^6 km^2. Ontario is bounded by the province of Quebec to the east, the province of Manitoba to the west, Hudson Bay and James Bay to the north, and the Great Lakes to the south. With a population of more than 13.5 million, Ontario is home to about 2 in 5 Canadians. More than 85% live in urban centers, largely in cities on the shores of the Great Lakes. It has been reported by Ontario Ministry of the Environment [*Ministry of the Environment (MoE)*, 2011a] that the average temperature in Ontario has gone up by as much as 1.4°C since 1948. Such a temperature increase may lead to large changes in the patterns of wind and precipitation [*Trenberth*, 2011]. As a consequence, local residents are seeing more frequent and intense weather anomalies in recent years. Climate change is becoming one of the most pressing issues challenging the Province of Ontario. In 2011, Ontario Ministry of the Environment [*MoE*, 2011b] released its adaptation strategy and action plan to create a vision and framework for collaboration across government, businesses, communities, institutes, and individuals, aiming at minimizing the damages caused by climatic changes through taking prudent actions in advance. Implementing such initiatives requires a thorough assessment of both the short-term and long-term effects of climate change for the entire province.

2.2. IDF Curves

In general, an IDF curve is produced through a statistical analysis of observed extreme rainfall events to present the probability of a given rainfall intensity and duration expected to occur at a particular location. The IDF curve can provide a convenient tool for analyzing and summarizing the essential characteristics of point rainfall for shorter durations, and it has been extensively applied in many hydraulic and hydrological engineering practices for design of structures that control storm water and flooding [e.g., *Alila*, 2000; *Borga et al.*, 2005; *Hogg et al.*, 1989; *Madsen et al.*, 2002, 2009; *Mailhot et al.*, 2007].

The development of IDF curve starts by gathering time series records of different durations. Annual extremes are then extracted for all durations from the time series. Typically, an IDF curve includes the frequency of annual extremes of rainfall intensity (unit: mm/h) or rainfall depth (unit: mm) typically corresponding to the following durations: 5, 10, 15, and 30 min and 1, 2, 6, 12, and 24 h. A probability distribution will be selected from the extreme value distributions (known as Fisher–Tippett types I, II, and III distributions) to fit the annual extremes,

Figure 1. Domain setup of the PRECIS experiments over Ontario, Canada.

such that the extreme rainfall intensity or depth at given frequency (known as return period) can be estimated for all durations. Return periods are usually expressed in years, and commonly used values of return periods in practice include 2, 5, 10, 25, 50, and 100 years. As a well-known type I distribution, Gumbel extreme value distribution has been widely accepted and used by Environment Canada [*Environment Canada*, 2012; *Hogg et al.*, 1989] and Canadian Standards Association [*Canadian Standards Association*, 2010], as well as many other national meteorological centers around the world [*Sevruk et al.*, 1981] to describe the frequency of extreme rainfall events. The Gumbel distribution is usually expressed as follows [*Hogg et al.*, 1989]:

$$X_{TD} = \mu_D + \mathrm{K}_T \sigma_D \tag{1}$$

where X_{TD} represents the exceedance value of rainfall intensity or depth of the T year event for a given duration D; μ_D and σ_D are the population mean and standard deviation of the annual extremes corresponding to the duration (D), which are usually estimated using the sample mean and standard deviation of available observations for annual extremes; and K_T is a frequency factor depending on the return period (T). Assuming that the observed annual extremes at given duration D is denoted as x_i ($i = 1, 2, 3 \ldots, N$), μ_D and σ_D can be estimated using the sample mean and standard deviation of available observations, as follows:

$$\mu_D = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{2}$$

$$\sigma_D = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu_D)^2}{N-1}} \tag{3}$$

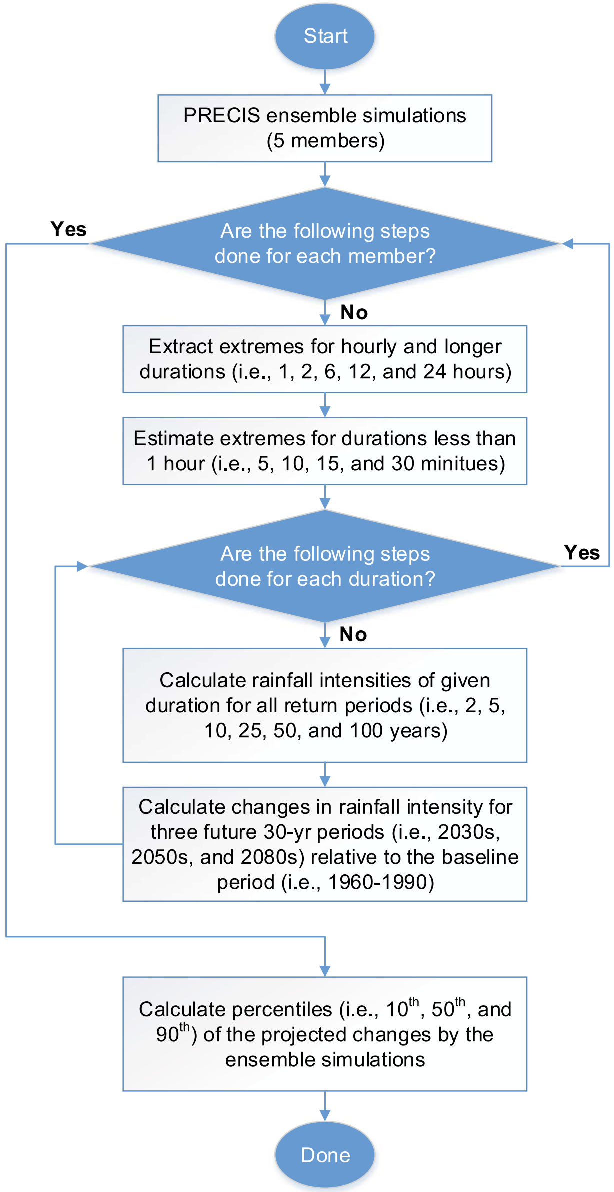

Figure 2. Flowchart for data processing.

The frequency factor can be calculated by the following equation:

$$K_T = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \ln\left\{\ln\left(\frac{T}{T-1}\right)\right\}\right] \quad (4)$$

For a given return period, its frequency factor can be obtained through equation (4). Thus, the exceedance values for all durations corresponding to the return period can be computed using equation (1). In reality, rainfall observations are only available for given durations. The IDF information calculated for those given durations is usually extended through interpolation to estimate the IDF values for other rainfall durations. In order to make the interpolation process more efficient, the IDF data derived with above method are typically fitted to a continuous function between rainfall intensity and duration. A three-parameter function will be used in this study according to the Drainage Management Manual issued by the *Ministry of Transportation of Ontario* [1997], as follows:

$$I_{TD} = \frac{A_T}{(D + B_T)^{C_T}} \quad (5)$$

where I_{TD} represents the exceedance value of rainfall intensity for given return period (T) and duration (D) and A_T, B_T, and C_T are the coefficients corresponding to the return period (T). These coefficients can be estimated through the method of least squares to achieve the closest possible fit of the data. For consistency, the rainfall duration (D) here is measured in hours. Once the IDF data are fitted to the function given by equation (5), curves of rainfall intensity versus duration for different return periods can be produced to help determine the average rainfall intensity likely to be attained or exceeded for a specific frequency of occurrence and a given duration.

3. Study Area and Data

As shown in Figure 1, the domain of PRECIS ensemble experiments covers the entire territory of Ontario with a spatial resolution of 25 km. There will be a large volume of climate projections generated for ~1900 grid cells over both land and water in the context of Ontario. Considering that the IDF analyses are usually applied for summarizing the characteristics of extreme rainfall events at a single point, this study will be focused on analyzing the impacts of climate change on the IDF curves for the City of Toronto. Analysis for all grid cells over the entire province has been carried out in a similar way, and their projected IDF curves are made available at the Ontario Climate Change Data Portal (http://ontarioccdp.ca). Toronto is the provincial capital of Ontario, and it is the largest and most populous city in Canada. The City of Toronto was built with complex underground pipes, sewers, and catch basins and is now facing a large number of challenges due to the

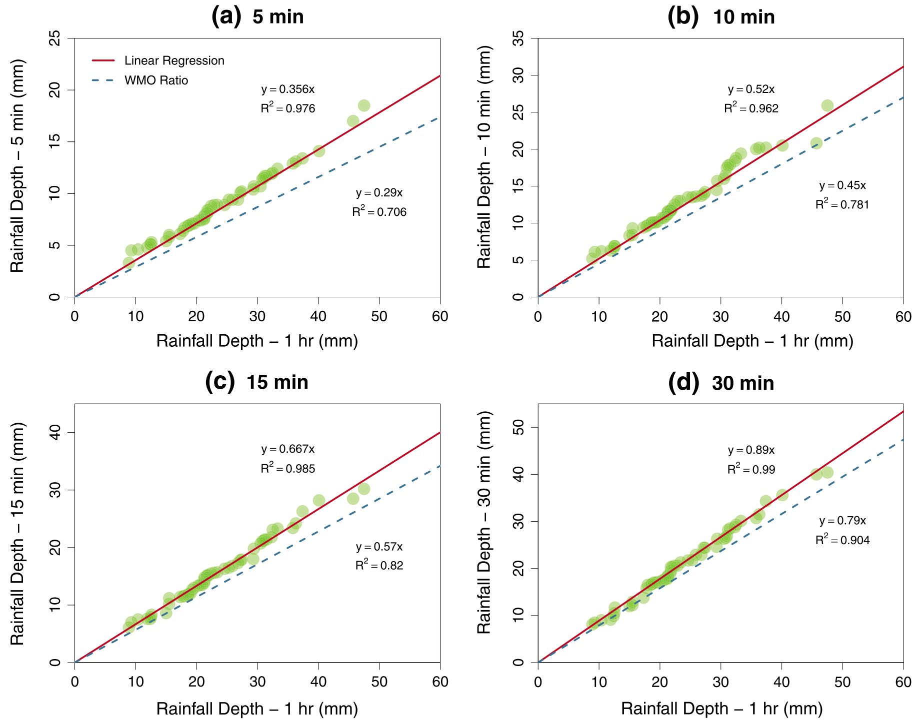

Figure 3. Regression analysis for extreme rainfall depth between short durations and 1 h duration.

heavy rainfall, melting snow, and runoff associated with climate change. Among them, basement flooding has become a common issue for the homeowners in recent years. To help deal with the problem, the city council has approved a bylaw making it mandatory for property owners to disconnect their downspouts from the sewer system in order to reduce the risk of basement flooding by releasing rainwater into the local waterways [*City of Toronto*, 2014]. Following that, a multiyear program, named Basement Flooding Protection Program, has been initiated from 2011 to help reduce the risk of future flooding by making improvements to the city's sewer system and overland drainage routes. Effective assessment of the potential changes in the extreme rainfall events in terms of both frequency and intensity is therefore necessary for supporting the decision making and engineering practices related to such a multiyear initiative.

The PRECIS simulations over the City of Toronto are extracted and sliced into four 31 year periods: one baseline period and three future periods (i.e., 2030s, 2050s, and 2080s), representing the climate projections under both current and future forcing conditions. Steps of data processing and calculating the projected changes by the PRECIS ensemble simulations are detailed in Figure 2. The highest temporal resolution of PRECIS outputs is 1 h. In order to obtain annual extremes for durations less than 1 h (i.e., 5, 10, 15, and 30 min), indirect estimation methods should be employed. A method by World Meteorological Organization [*World Meteorological Organization (WMO)*, 1994] suggests that extreme rainfall amounts for short durations less than 1 h can be estimated by multiplying the 1 h extremes by fixed ratios. The average ratios of rainfall extremes for 5, 10, 15, and 30 min to 1 h amounts are 0.29, 0.45, 0.57, and 0.79, respectively. These ratios are computed from hundreds of station year of records with an average error of less than 10% [*WMO*, 1994]. Since the fixed ratios provided by WMO are averaged values at many gauged weather stations throughout the world, applying them to a specific area without any adjustments may lead to biased estimation of the annual rainfall extremes for short durations. Hence, we conduct regression analysis of the annual extremes for short durations versus that of 1 h using the lengthy observations at the weather station of Toronto Lester B. Pearson International Airport (hereinafter referred to as TLA). The observed extremes for TLA are obtained from the Engineering Climate Data Sets of Environment Canada (available at http://climate.weather.gc.ca/prods_servs/engineering_e.html). Figure 3 shows the comparison of fitting results between linear regression and WMO ratios. Apparently, the WMO fixed ratios shows poor performance in fitting the relationships of annual extremes of short durations versus that of 1 h. We therefore apply the ratios obtained through linear

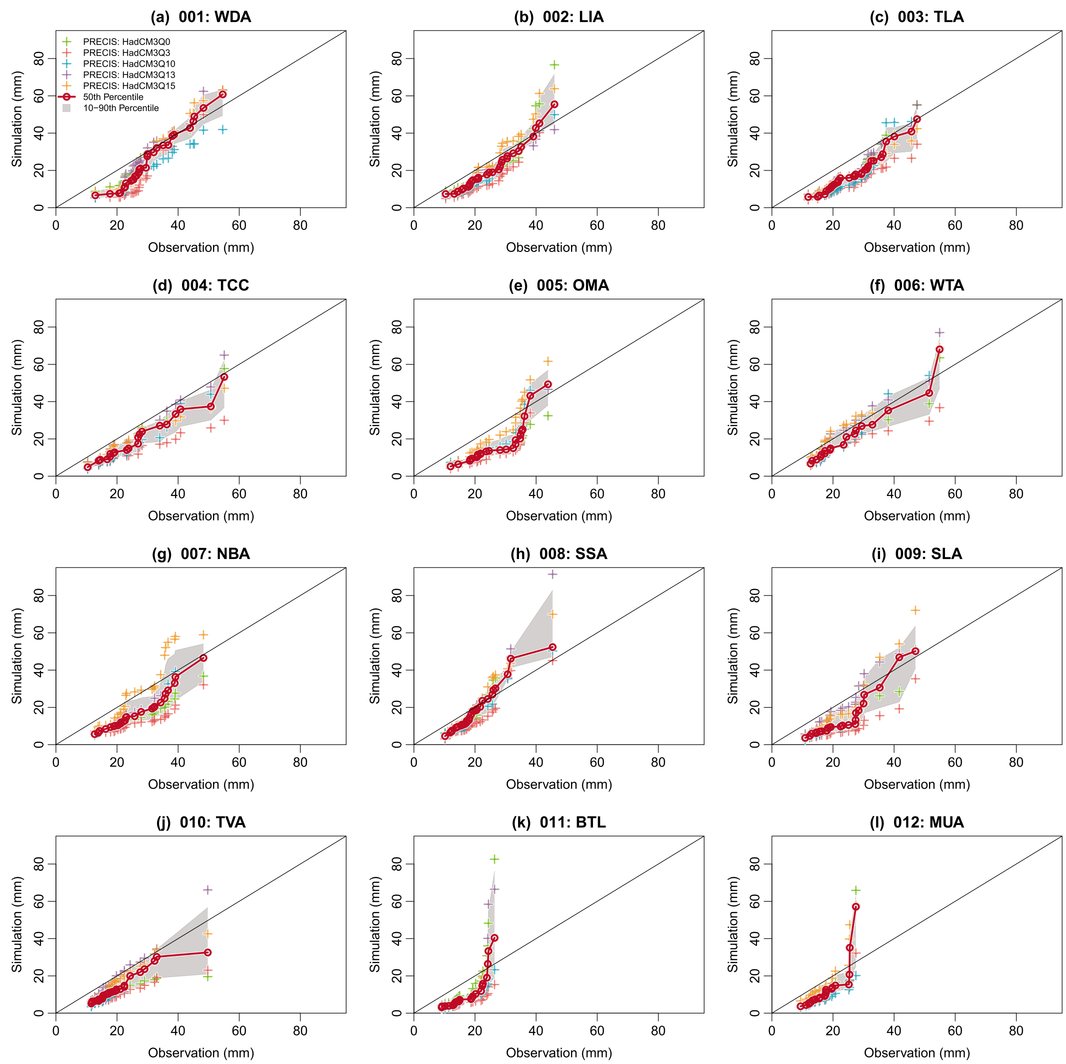

Figure 4. Q-Q plots for extreme events with a duration of 1 h.

regression (i.e., 0.356, 0.52, 0.667, and 0.89) in this study to estimate the future projections of annual extremes for durations less than 1 h in the City of Toronto.

4. Results

4.1. Validation

The annual rainfall extremes for available durations (i.e., 1, 2, 6, 12, and 24 h) simulated by the PRECIS ensemble experiments are extracted for both the baseline and future periods. In order to synthesize the simulations by the PRECIS ensemble, we use the type 7 algorithm defined by *Hyndman and Fan* [1996] hereinafter to derive quantiles through a piecewise linear interpolation. Following the approach used in UK Climate Projections science report [*Murphy et al*., 2009], we used three typical quantiles (or percentiles) of the PRECIS ensemble simulations to summarize the possible outcomes of future projections. In detail, the median (namely, the 50th percentile) is used here to represent the central value of the distribution, indicating that half of the members are less than or equal to it; the 10th percentile is used to describe the ensemble projections by saying very likely to be greater than or very unlikely to be less than, while the 90th percentile is to indicate very likely to be less than or very unlikely to be greater than. The range bounded by the 10th and 90th percentiles is denoted as 10–90th percentile range, and we regard it as an interval that the PRECIS simulations are most likely to fall in or most unlikely to go beyond.

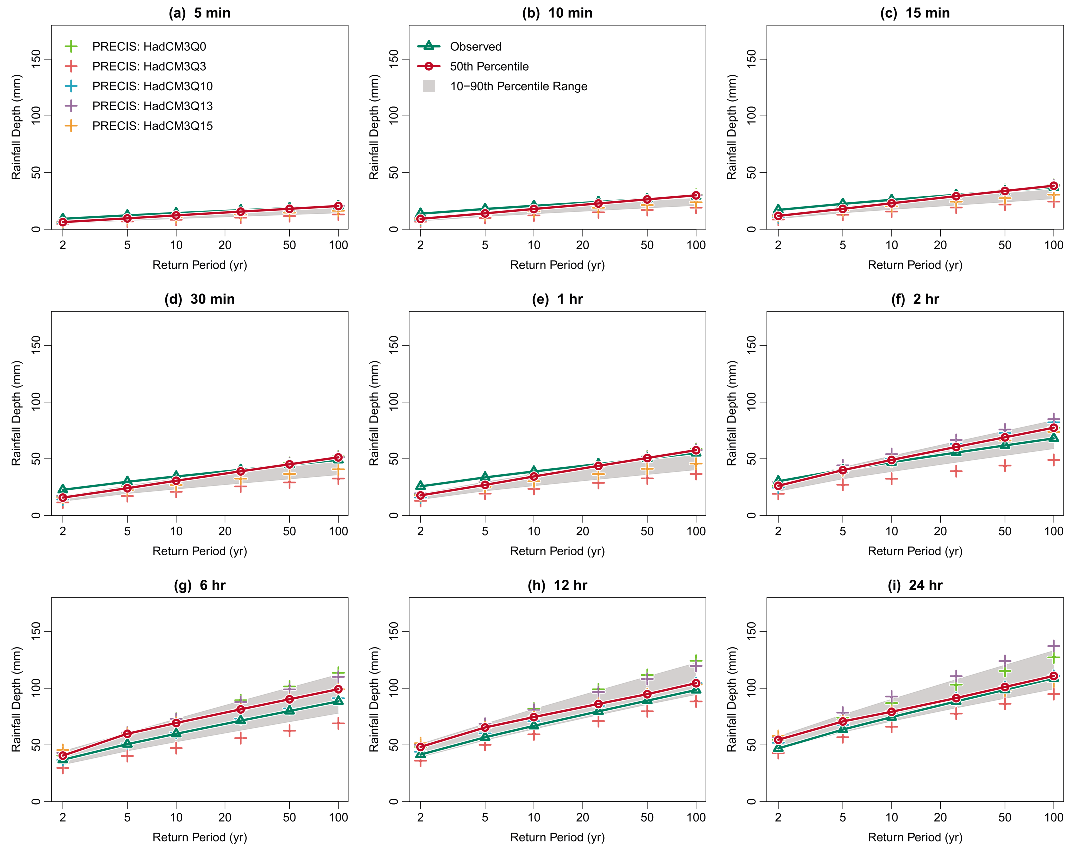

Figure 5. Comparison of rainfall depth for the baseline period at the station of TLA.

The simulated extremes for the baseline period are first compared to the observed ones at 12 weather stations which are geographically distributed across the landmass of Ontario (see Table S1 in the supporting information), with the purpose of validating the performance of the PRECIS ensemble in reproducing spatial variations in rainfall extremes. Figure 4 shows the quantile-quantile (Q-Q) plots between the simulated extremes with a duration of 1 h and the observed ones for the baseline period. The Q-Q plots for other durations (i.e., 2, 6, 12, and 24 h) are shown in Figures S1–S4 in the supporting information. Q-Q plots are often used to determine if two data sets come from populations with a common distribution [*Barnett*, 1975]. Here we use Q-Q plots to visually check whether the distribution of the observed extremes can be well captured by the ensemble simulations. It seems that each station tells a different story from others in terms of their quantile patterns. However, the 50th percentile line and the 10–90th percentile area at most of the stations are aligned closely to the diagonal line. For example, the comparisons for 1 h duration show that the observed extremes at 10 of the 12 stations are well captured by the ensemble simulations, except for the stations of BTL and MUA, where the simulations tend to overestimate the extremes with amounts greater than 25 mm. It is also reported that the observed extremes for other durations at a few stations are likely to be overestimated or underestimated by the ensemble simulations. Nevertheless, the good fittingness to the distribution of observed extremes at most of the stations demonstrates that the ensemble simulations perform well in capturing the spatial variations of rainfall extremes in the context of Ontario.

The rainfall depths for durations of 1, 2, 6, 12, and 24 h with different return periods can be estimated by fitting the Gumbel extreme value distribution as given in equation (1) with direct outputs of the PRECIS ensemble. The annual extremes for other durations shorter than 1 h are estimated by multiplying the simulated annual extremes for 1 h by constant ratios obtained through the regression models as shown in Figure 3, such that the rainfall depth for these durations can be estimated. Thus, we can obtain the simulated rainfall depths at all durations for both baseline and future periods. Figure 5 shows the rainfall depths of all durations with different return periods for the station of TLA. The 50th percentiles for 2, 6, 12, and 24 h are close to the observed rainfall

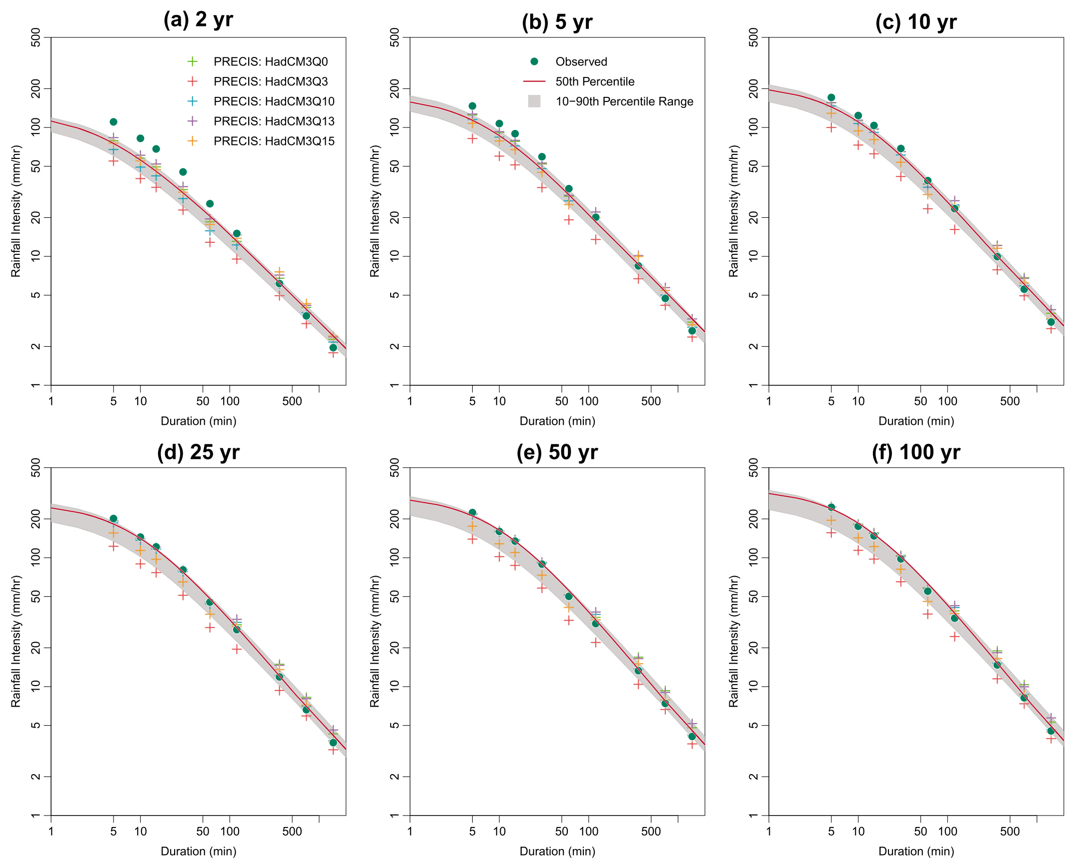

Figure 6. Comparison of rainfall intensity for the baseline period at the station of TLA.

depths for all return periods (with slight overestimations), and the observed ones can be well covered by the 10–90th percentile range. In contrast, the simulated rainfall depths for 1 h slightly underestimate that of the observations for return periods of 2, 5, and 10 years. Similar underestimations for durations shorter than 1 h are also reported as their annual extremes are estimated by applying constant ratios to the 1 h extremes.

Rainfall intensities for different durations can be derived from the simulated rainfall depths. They are then fitted into a continuous function as given by equation (5). Figure 6 shows the simulated rainfall intensities versus various durations for all return periods calculated from the ensemble experiments and the observations for the baseline period. It is reported that the observation-based rainfall intensities for return periods of 5, 10, 25, 50, and 100 years are well captured by the median values from the PRECIS ensemble. However, the simulated rainfall intensities with a 2 year return period tend to underestimate the observed ones for short durations (i.e., 5, 10, 15, and 30 min and 1 h).

4.2. Projected IDF Curves

The rainfall intensities versus various durations at given return periods for three future periods (i.e., 2030s, 2050s, and 2080s) are shown in Figures 7–9. Among the 5 members of the ensemble, the PRECIS simulation driven by HadCM3Q15 projects the highest rainfall intensities for the three future periods, while the one driven by HadCM3Q3 projects the lowest rainfall intensities. However, the simulation driven by HadCM3Q15 generates relatively low rainfall intensities in the baseline period while compared to those projected by other members. In general, the 10–90th percentile ranges of rainfall intensities for future periods are likely to become wider than that of the baseline period, which to some extent indicates that greater uncertainty will be introduced while modeling future climate change. In addition, an overall increasing trend in the rainfall intensities versus various durations for all return periods is revealed from 2030s to 2080s.

To further evaluate how the future rainfall intensities will change, we extract the 50th percentiles of the ensemble projections for four 31 year periods and calculate the future changes relative to the baseline period.

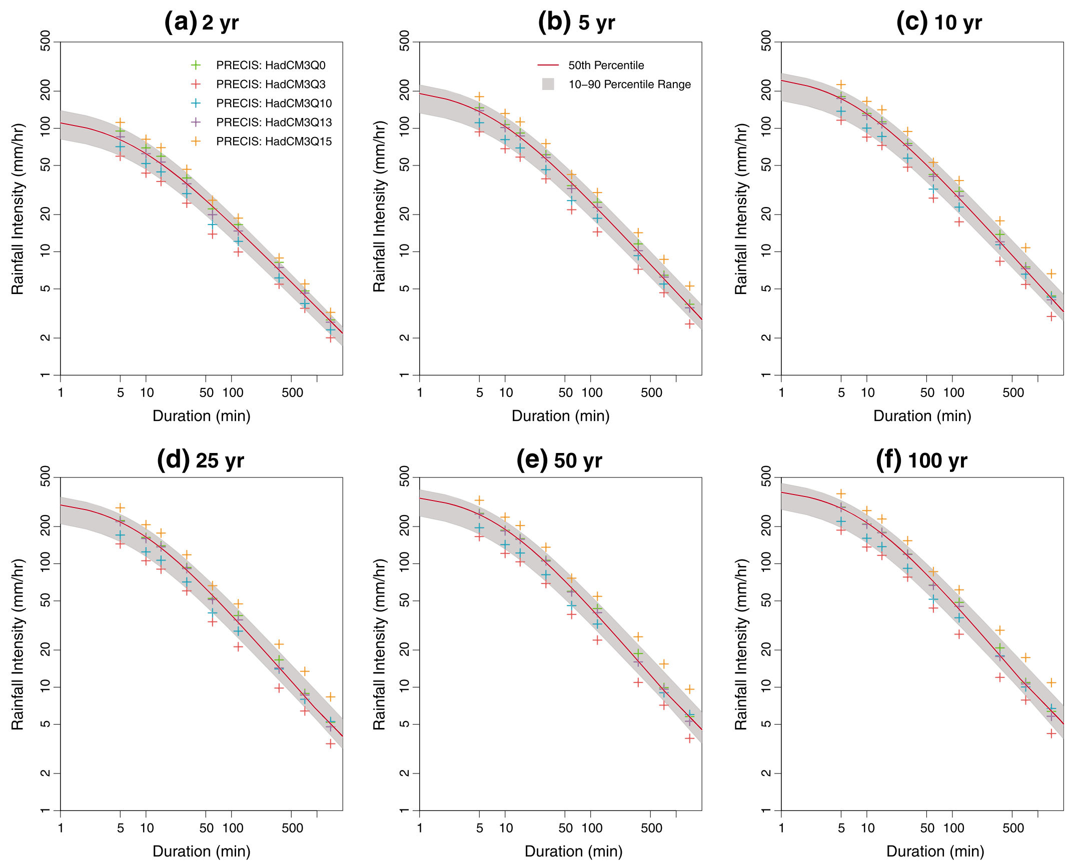

Figure 7. Projected rainfall intensity in 2030s for the City of Toronto.

Figure 10 shows the comparisons of the projected rainfall intensities between future and baseline periods in terms of the 50th percentiles (indicated by the colored bars) and 10–90th percentile ranges. Apparently, there is an overall rising trend in the 50th percentiles of projected rainfall intensities with time. Meanwhile, the 10–90th percentile ranges are getting wider with time. This further supports our hypotheses based on the results shown in Figures 7–9. However, we should note that the medians of projected rainfall intensities for 2050s are likely to be equal to or less than that of 2030s, which may suggest that the ensemble simulations would project a temporary decrease in rainfall intensities in the middle of this century after an evident increase in the next few decades. But a remarkable increase is likely to appear to the end of this century which leads to an overall increasing trend throughout the century. However, we should note that using a single large-scale forcing model (i.e., HadCM3) to drive the PRECIS simulations may lead to less distinct ensemble members from each other than those driven by completely different models [*Salathé et al*., 2014]. Thus, the temporary decrease in the 2050s probably should be considered as one possible realization of future decadal variability simulated by the HadCM3 rather than an explicit prediction of the sequencing in extreme events.

Figure 11 shows the projected IDF curves for the City of Toronto under both current and future forcing conditions. The 50th percentiles for projected rainfall intensities versus the given durations (indicated by up triangle points) are used to fit the three-parameter function as given by equation (5), such that rainfall intensities for other durations can be directly estimated. The IDF curves perform well in terms of fitting the projected rainfall intensities for given durations, except for a slight overestimation for those projected values of 1 h duration. The rainfall intensities for different combinations of return period and duration can be estimated based on the IDF curves. For example, the median value of projected rainfall intensity for 100 year return period and 24 h duration is around 5 mm/h for the baseline period, but the median value for the same combination in 2080s is likely to rise to as high as 8 mm/h.

To further estimate the projected changes in extreme rainfall intensities by the PRECIS ensemble, we calculate the 50th percentile of changes projected by each member of the ensemble and use it as the central

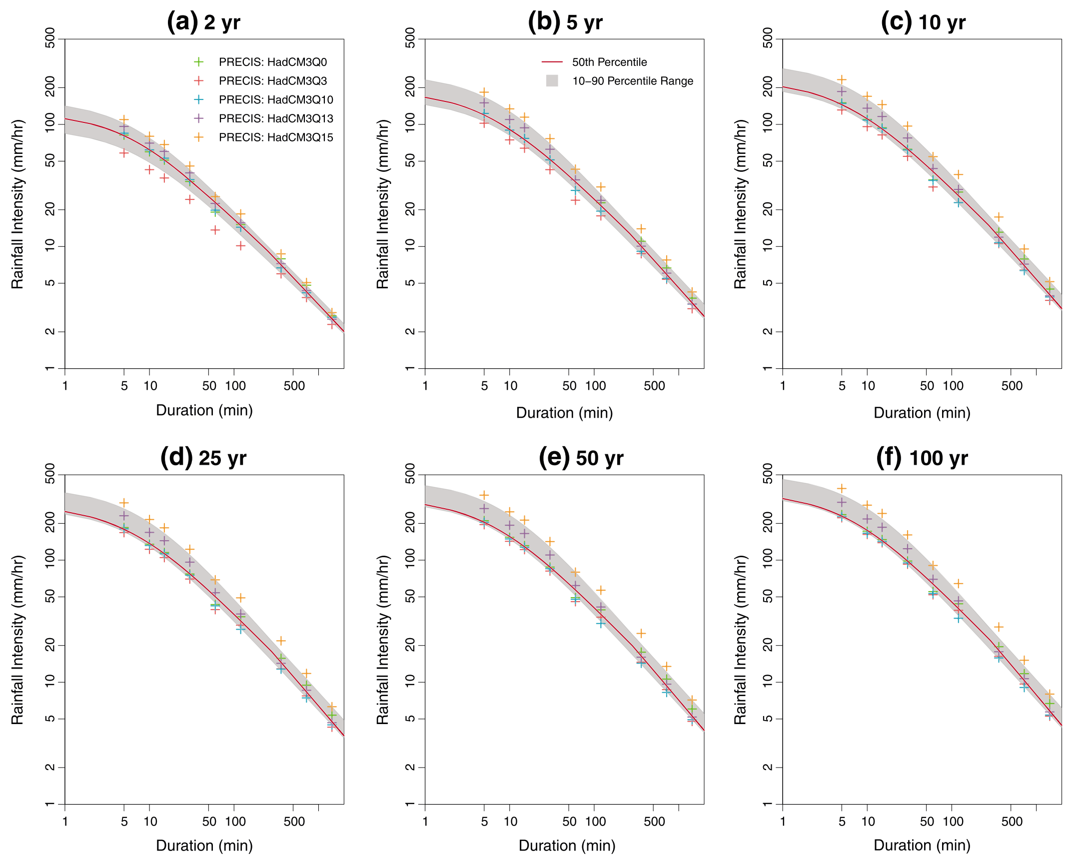

Figure 8. Projected rainfall intensity in 2050s for the City of Toronto.

estimate for the plausible change in rainfall intensity. Figure 12 shows a changing map which summarizes the median changes in the projected rainfall intensities for future periods relative to the baseline period. The changes are presented as relative percentages, and positive values indicate percentage increases relative to the baseline projections, whereas negative ones indicate percentage decreases. The changing map reports that the PRECIS ensemble is likely to project an overall increasing pattern in the intensities of all extreme rainfall events, except for a very small decrease by 0.2% in the intensity of a 2 year event over a 5 min duration in 2030s. The projected changes in rainfall intensities for all durations also show an apparent increasing trend with time. In particular, the medians of percentage change for 2030s are mostly in the range of 5% and 17%, the median changes for 2050s are mainly ranging from 11% to 22%, and the median changes for 2080s mainly vary between 25% and 50%. In addition, there is an increasing trend for the percentage changes in rainfall intensities with the return periods from 2 to 100 years. In other words, the shorter the return periods, the smaller the percentage changes. For example, the most evident changes are projected for the 100 year rainfall extreme events in 2080s, when the smallest median change would be 41.2% (for 15 min duration) and the biggest median change can be as high as 51.7% (for 24 h duration).

5. Conclusions

In this study, a regional climate modeling approach based on the PRECIS modeling system was proposed for investigating the potential impacts of climate change induced by increased GHGs on the intensity and frequency of extreme rainfall events in the context of Ontario, Canada. In detail, a 5-member RCM ensemble with a fine resolution of 25 km was first developed by using the selected members of the QUMP provided by UK Met Office Hadley Centre as boundary conditions to drive the PRECIS model, with the purpose of generating more reliable projections for future climate change. The Gumbel distribution was then applied to fit the probability of occurrence of extreme rainfall events, such that the rainfall intensities for various

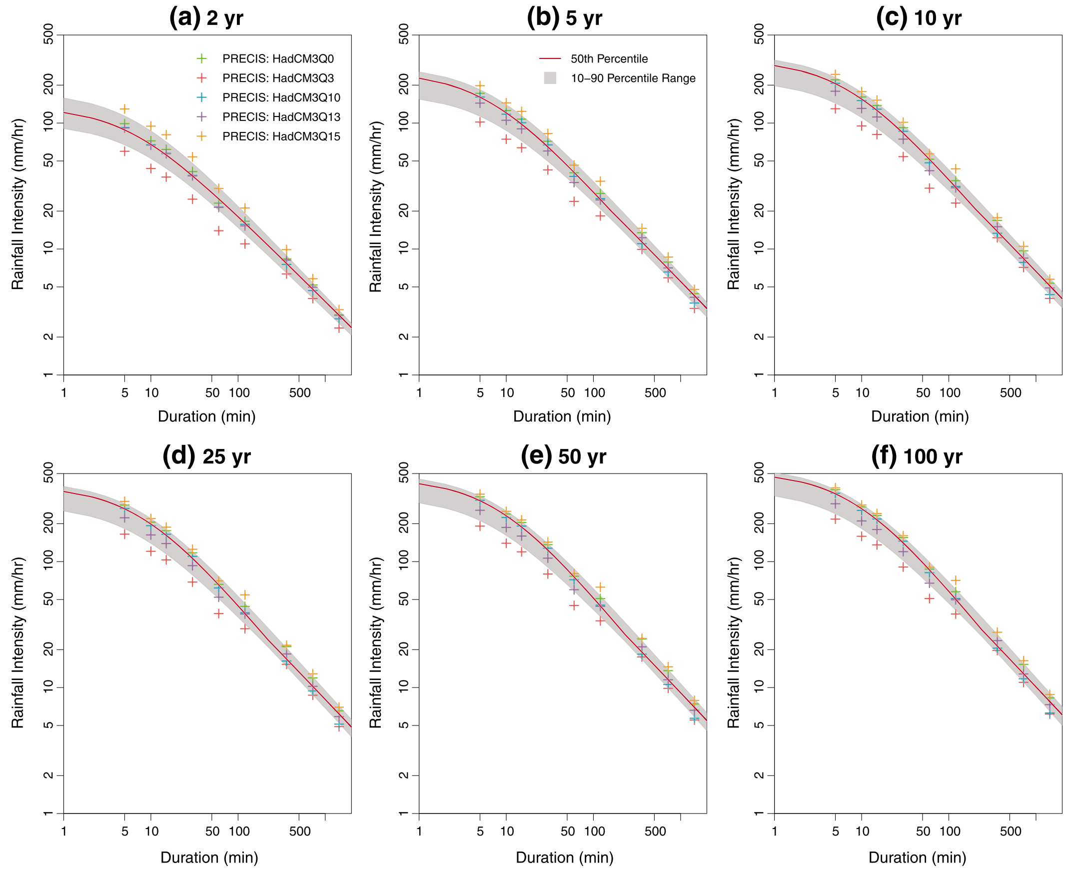

Figure 9. Projected rainfall intensity in 2080s for the City of Toronto.

durations (i.e., 5, 10, 15, and 30 min and 1, 2, 6, 12, and 24 h) with different return periods (i.e., 2, 5, 10, 25, 50, and 100 years) can be estimated. The projected IDF curves at all 25 km grid points over the Province of Ontario were developed and made available for download at a public data portal. Only detailed analyses on the projected IDF curves for the City of Toronto were presented in this paper.

The high-resolution projections generated by the PRECIS ensemble were extracted for both the baseline and future periods. The simulated rainfall annual extremes for the baseline period were compared with the observations from 12 gauged weather stations to validate the performance of the ensemble in reproducing the observed extremes. Following that, the rainfall projections for future periods were used to develop projected IDF curves in 2030s, 2050s, and 2080s, as well as to calculate their changes relative to the baseline period. The results reported that intensities of rainfall extreme events versus various durations with different return periods were all likely to increase over time. Such a consistent increase would lead to an overall uplift in the exceedance values of rainfall intensity of extreme events, implying that intense rainfall events were likely to occur more frequently in the future. In addition, more significant changes in the rainfall intensity were projected for extreme events with longer return periods at all given durations. For example, the median changes of the rainfall intensity for 2 year extreme events were projected to be varying between 18.3% and 29.4% for different durations in 2080s, while bigger changes (ranging from 41.2% to 51.7%) were more likely to happen for 100 year extreme events to the end of this century.

This paper presented an effective approach for assessing the climate change impacts on both the intensity and frequency of extreme rainfall events by integrating regional climate modeling and development of IDF curves into a general framework. However, we should note that the achievements of this paper still depend on a number of limitations or assumptions that may impose severe caveats on their applications in engineering design and risk assessment. First, the high-resolution climate projections for the study area were developed based on the data sets of Coupled Model Intercomparison Project (CMIP) phase 3 forced by

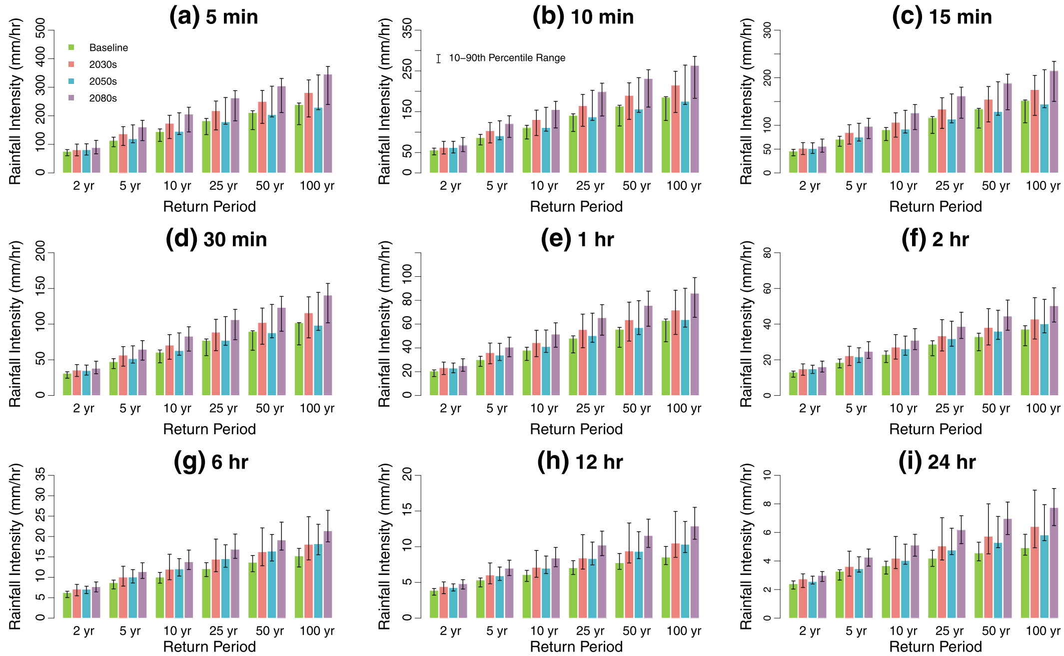

Figure 10. Comparison of rainfall intensity between future and baseline periods for the City of Toronto.

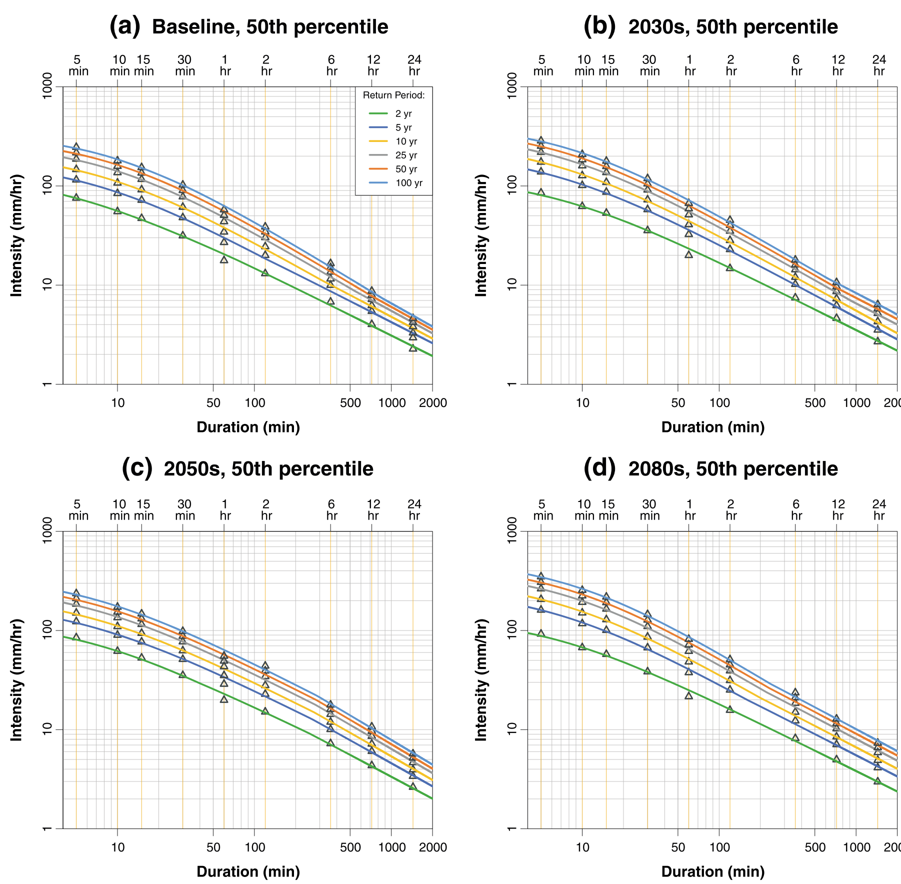

Figure 11. Projected IDF curves for the City of Toronto.

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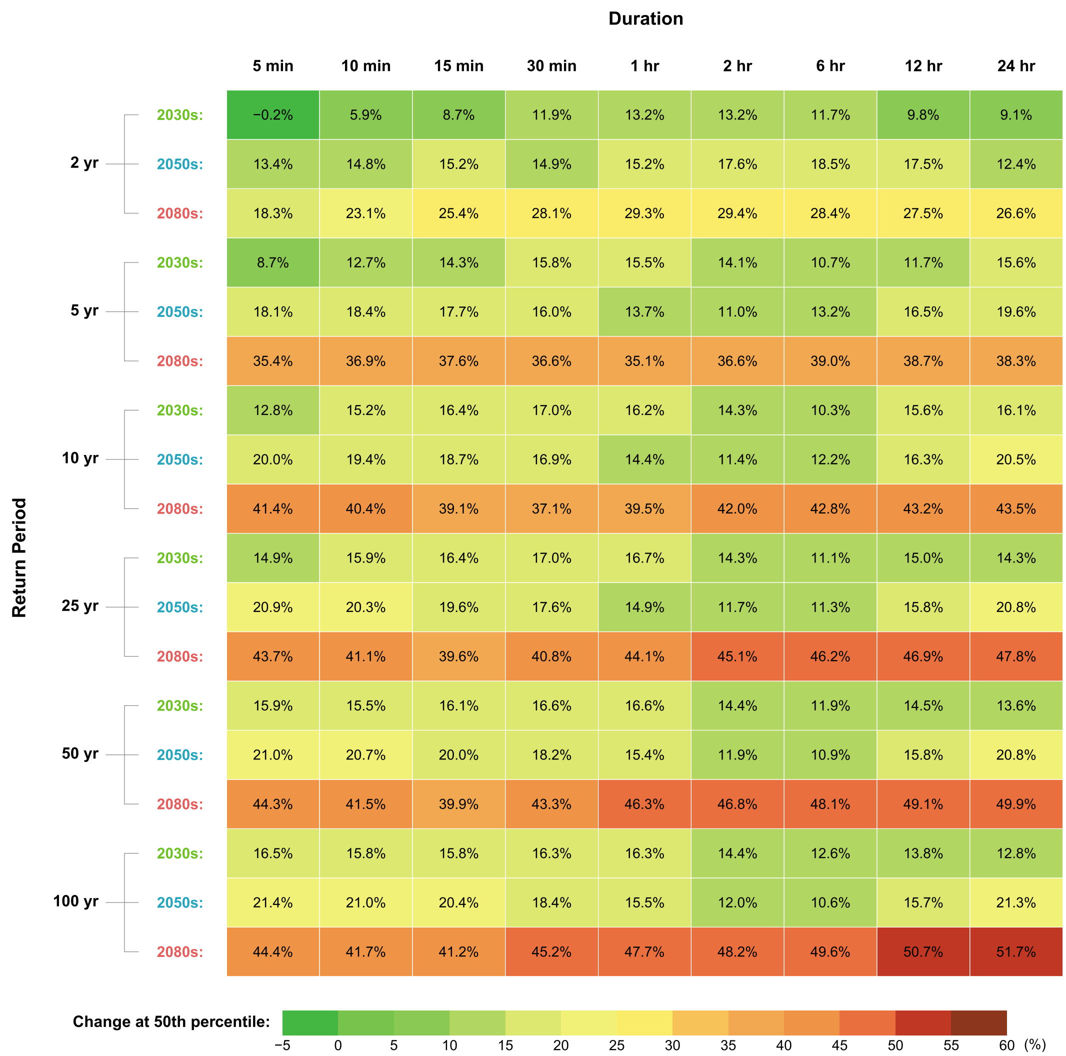

Figure 12. Projected changes in rainfall intensity for the City of Toronto.

the SRES emissions scenarios. With the release of CMIP5, further efforts on updating the climate projections and the projected IDF curves using the new data sets are needed. Second, this study adopted only one extreme distribution function (i.e., Gumbel) to fit the probability of occurrence of extreme rainfall events. Even though this function was recommended to be used for the study area by Environment Canada, it may be subject to some unexpected changes in the context of climate change. Applicability of other extreme value distributions (e.g., generalized extreme value distribution [*Potter and Lettenmaier*, 1990]) for developing future projected IDF curves in the context of study area should be further investigated. Note that estimating the occurrence of extreme events with a longer return period (e.g., the 100 year event) than the length of observations or simulations (e.g., 31 year simulations) may involve inherent uncertainties due to the choice of extreme value distributions. Third, the PRECIS simulations are driven by a single large-scale model (i.e., HadCM3), which may lead to less uncertainties associated with the results as the ensemble members are likely to be less distinct from each other than those driven by completely different models[*Salathé et al.*, 2014]. Next, improvements to the spatial resolution of RCM simulations and to the accuracy of observational data are still required to allow capturing small-scale but high-intensity extreme storms. For example, regional models with higher spatial resolution may be introduced to simulate the interactions among many factors that are affecting extreme storms at local scales; alternate observed data sets (e.g., corrected radar data) may be needed to help validate extreme storms simulated by high-resolution RCMs. Finally, the annual rainfall extremes for short durations less than 1 h (i.e., 5, 10, 15, and 30 min) are usually not available from the direct output of RCMs. Here we fitted the relationship between observed rainfall extremes for short durations and that of 1 h duration using different linear regression models with fixed ratios. These ratios were assumed to be time independent and thus would not change with time. We then applied the ratios to the 1 h annual extremes simulated by the PRECIS ensemble such that extremes for short durations can be estimated. But these ratios might also be subject to change in the context of climate change. Using weather generators [e.g., *Kilsby et al.*, 2007; *Semenov and Barrow*, 1997] for developing high-resolution climate projections of short durations seems to be more realistic and therefore is worthy of further exploration. However, the results presented in this paper are still important for local practitioners and decision makers from a planning perspective.

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